



BACHELOR'S DEGREE IN AEROSPACE VEHICLE ENGINEERING

Bachelor Thesis

ANALYTICAL STUDY OF SPACEX MISSION ARCHITECTURE TO REACH MARS

Report

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ABSTRACT

Space is going through a new evolution, where the objectives are much more ambitious than before thanks to the new technologies. The possibilities that arise from these new achievable projects are grateful, such as creating human stations in satellites, or even building cities for human being in other planets. In order to achieve these goals, the biggest problematic currently is the transport method, that is to say, how to reach distant celestial bodies in a viable way, focusing on both the feasibility for the human life and the economic aspects, and the first proposal is to reach Mars.

To do so, a patched conic approximation will be performed so as to analyse the Earth to Mars interplanetary transfer. By using a Newton-Raphson iterative process, which includes a continuation method with a differential corrector, the Lambert problem will be solved in order to obtain the main results. It will also be done a main-materials estimation for the Mars society competition, defined as a case study of the project.

On the other hand, the privatization of the space sector is adding new players to the game, and as a result of this, a new space race is taking place. The most outstanding players nowadays are NASA, on the side of government agencies, and SpaceX, from the private space sector. Both companies have presented strategies to reach the red planet, and this study is focused on the architecture analysis of the SpaceX mission, in order to analyse each of its phases, to compute the trajectory and to develop a preliminary study of the re-entry manoeuvre.

Furthermore, due to the current situation, in which the interest of the manned interplanetary journeys is booming, it is important to define the suitability of the whole mission. Because of the high investment required for conducting a Mars' colonization process, a preliminary materials budget and a first iteration of the total cost of the program will be conducted, trying to roughly quantify the amount necessary to develop the project globally.

Keywords: Space sector, SpaceX, Starship, Architecture analysis, Trajectory simulation, Analysis of the alternatives.

DECLARATION OF HONOR

I declare that,

the work in this Bachelor Thesis is completely my own work,
no part of this Bachelor Thesis is taken from other people's work without giving them credit,
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Title of the Bachelor Thesis: **Analytical Study of SpaceX Mission Architecture to reach Mars**

Signed:

Oscar Macía,

June, 30th 2020

Bachelor's Degree in Aerospace Vehicle Engineering

ACKNOWLEDGMENTS

Life consists of a set of stages which a person goes through – even without considering it, day after day the time is inexorably moving, and it is a must to seize every moment. This stage has been incredible for me, I have been discovering new things every day. I was not especially a fan of the aircrafts or the space, I was just curious about how is possible to make an object weighting tones capable of flying or orbiting, among other space related things, and as I said, during these years I have learnt the answers to these questions and many more, and, something I think it is even more important, I have discovered new questions to which look for answer. Therefore, I am really proud of the decision I made regarding the bachelor's degree choice.

To begin with, I would like to thank my family and friends for all they have done for me during these last four years. Together we have been through difficult situations and, no matter what or how, we have been able to succeed in all of them. It is important to remark that I am not only talking about difficulties in the studies, but I am referring to life situations that come to you, such as the loss of loved ones, or the social distancing due to the different paths that each one follows in his/her own life. Nevertheless, in every moment I felt I could not, they showed me that giving up was not an option, and we managed to keep going, so I want to thank all of you.

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TABLE OF CONTENTS

Abstract.....	ii
Declaration of honor.....	iii
Acknowledgments	iv
Table of contents	v
Table of figures.....	vii
Table of tables	ix
Table of abbreviations and symbols	x
1 Introduction.....	1
1.1 Aim	1
1.2 Scope.....	1
1.3 Requirements	4
1.4 Justification.....	4
2 Background.....	6
2.1 State of the art.....	6
2.2 Theoretical framework.....	7
2.2.1 Fundamentals of Astrodynamics	7
2.2.2 Basic orbital manoeuvres.....	9
2.2.3 Orbit determination and trajectory computation.....	11
2.2.4 Orbital elements obtainment.....	15
2.2.5 Patched Conic Approximation.....	17
2.2.6 Ascent and entry study.....	19
2.2.7 Tsiolkovsky equation.....	20
2.3 SpaceX Company	21
3 SpaceX mission analysis and synthesis	23
3.1 Key mission goals.....	23
3.2 Mission timeline	24
3.3 Analysis of mission architecture.....	27
3.3.1 Preliminary mission analysis and feasibility study.....	27
3.3.2 Deep study of each phase of the mission.....	30
3.3.3 Architecture Analysis Tool.....	33
4 Architecture proposal study	42
4.1 Mars' colonization process	42
4.2 Global results	44
4.3 Complete study for period 2037-2039	47
5 Dedicated spacecraft subsystems description.....	54
5.1 Propulsion system	54
5.2 Spacecraft	56

5.3	Launch and assembly facilities	60
5.4	Attitude sensing and control system	60
5.5	Electrical power generation and storage	63
5.6	Fuel generation on Mars surface	64
6	Mars society competition case study	65
7	Economic plan	69
8	Environmental analysis	72
8.1	Environmental impact	72
8.2	Economic impact	72
8.3	Safety impact	73
9	Conclusions, improvements and recommendations	74
9.1	Conclusions	74
9.2	Improvements and recommendations	75
10	References	76

TABLE OF FIGURES

Figure 1. Orbital elements of a Keplerian orbit [20].....	8
Figure 2. Basic Hohmann transfer [20].....	10
Figure 3. Type I and Type II trajectories [7]	12
Figure 4. Newton-Raphson illustration [10].....	13
Figure 5. Trajectory iterative illustration [10]	13
Figure 6. Patched Conic Approximation transfer representation [12].....	17
Figure 7. Hyperbolic departure trajectory illustration [12].....	18
Figure 8. Evolution of the SpaceX concept of the Martian city [11]	24
Figure 9. Timeline of Starship Program.....	25
Figure 10. Preliminary mission analysis trajectory.....	29
Figure 11. Diagram of the mission architecture [11]	31
Figure 12. Launch phase.....	31
Figure 13. Refuelling phase.....	31
Figure 14. Starship Mars transfer.....	32
Figure 15. Mars entry and landing.....	32
Figure 16. Preparing return to Earth from the Martian surface	32
Figure 17. Departure from Mars and arrival to Earth	33
Figure 18. Global Lambert solver flow chart.....	34
Figure 19. Detailed Lambert solver flow chart.....	34
Figure 20. Launch windows obtainment flow chart.....	35
Figure 21. Hyperbolic trajectory flow chart	36
Figure 22. Rendezvous study flow chart.....	38
Figure 23. Entry study flow chart.....	41
Figure 24. Mars' population evolution.....	43
Figure 25. Initial velocity impulse porkchop plot 2022-2024 [M1].....	44
Figure 26. Initial velocity impulse porkchop plot 2025-2027 [M2].....	45
Figure 27. Initial velocity impulse porkchop plot 2027-2050 [M3].....	45
Figure 28. Porkchop plot 2037-2039 total impulse velocity	47
Figure 29. Porkchop plot 2037-2039 initial impulse velocity.....	47
Figure 30. Porkchop plot 2037-2039 final impulse velocity.....	48
Figure 31. Interplanetary transfer illustration.....	48
Figure 32. Escape hyperbolic trajectory.....	49
Figure 33. Arrival hyperbolic trajectory.....	50
Figure 34. Starship launching study.....	51
Figure 35. Refuelling rendezvous manoeuvre	52
Figure 36. Ballistic entry study	53
Figure 37. Manoeuvring entry study	53
Figure 38. SpaceX Super Heavy rocket [11].....	55
Figure 39. SpaceX Raptor engine [5].....	55
Figure 40. Starship in-space propulsion configuration [11]	56
Figure 41. Starship crewed (left) and uncrewed (right) configurations [5]	57
Figure 42. Starship internal structure [5].....	58
Figure 43. Starship in-space applications [5].....	59
Figure 44. Starship Mk1 at Boca Chica [2].....	60
Figure 45. SpaceX Cape 39A adapted for Starship [2].....	60

<i>Figure 46. Spacecraft Sensors.....</i>	<i>61</i>
<i>Figure 47. Starhopper thrusters [2]</i>	<i>62</i>
<i>Figure 48. Starship solar panels and battery pack [4]</i>	<i>63</i>
<i>Figure 49. Main materials price evolution.....</i>	<i>70</i>

TABLE OF TABLES

Table 1. Main properties of the conic sections.....	9
Table 2. SpaceX contracts assigned by NASA.....	22
Table 3. Orbital parameters of the transfer orbit.....	28
Table 4. Results obtained for the preliminary mission analysis.....	28
Table 5. Fuel consumption preliminary estimation.....	30
Table 6. Inputs required for launching study.....	37
Table 7. Earth standard atmosphere parameters.....	39
Table 8. Mars atmosphere model lower layer parameters calculation.....	40
Table 9. Mars atmospheric model upper layer parameters calculation.....	40
Table 10. Main milestones to complete during Mars' colonization.....	42
Table 11. Mars' population per milestone.....	43
Table 12. Global results for interplanetary transfers.....	46
Table 13. Interplanetary transfer data.....	48
Table 14. Interplanetary transfer orbital elements.....	49
Table 15. Hyperbolic escape and arrival main characteristics.....	50
Table 16. Rendezvous manoeuvre study data.....	51
Table 17. Total impulse velocity for performing refuelling manoeuvre.....	52
Table 18. Starship weight estimation and main materials weight.....	66
Table 19. Super Heavy rocket weight estimation and main materials weight.....	66
Table 20. Vehicles needed for conducting the architecture.....	67
Table 21. Main materials for building one unit of each type of vehicle.....	67
Table 22. Total mass for manufacturing all needed vehicles.....	68
Table 23. Cost estimation for each element considered.....	69
Table 24. Required quantity of Starships and Super Heavy rockets.....	70
Table 25. Main materials cost estimation.....	71
Table 26. Total cost.....	71

TABLE OF ABBREVIATIONS AND SYMBOLS

A	<i>Azimuth angle</i>	Φ	<i>State transition matrix</i>
\dot{A}	<i>Azimuth angle time-derivative</i>	ϕ	<i>Flight-path angle</i>
A_e	<i>Area at nozzle exit</i>	$\dot{\phi}$	<i>Flight-path angle time-derivative</i>
a_{HT}	<i>Semi-major axis of Hohmann transfer</i>	f_T	<i>Thrust fraction</i>
a_T	<i>Scale temperature gradient</i>	G	<i>G Lagrange coefficient</i>
β	<i>Sutherland's constant</i>	\dot{G}	<i>Derivative G Lagrange coefficient</i>
c	<i>Effective exhaust velocity</i>	g	<i>Gravity at concrete height</i>
CH_4	<i>Methane chemical formula</i>	g_0	<i>Earth nominal gravity</i>
δ	<i>Longitude</i>	γ	<i>Hyperbolic zenith angle</i>
$\dot{\delta}$	<i>Longitude time-derivative</i>	γ_T	<i>Specific heat ratio</i>
Δm_f	<i>Burnt propellant ejected</i>	H	<i>Hyperbolic anomaly</i>
Δv	<i>True anomaly difference</i>	H_0	<i>Initial hyperbolic anomaly</i>
ΔV	<i>Velocity impulse</i>	\mathbf{h}	<i>Angular momentum vector</i>
Δv	<i>Velocity propulsive impulse</i>	h	<i>Spacecraft height</i>
ΔV_A	<i>Impulse velocity at departure planet</i>	i	<i>Orbit inclination</i>
ΔV_B	<i>Impulse velocity at arrival planet</i>	I_{SP}	<i>Specific impulse</i>
ΔV_{tot}	<i>Total impulse velocity</i>	λ	<i>Latitude</i>
δx	<i>Deviation vector</i>	$\dot{\lambda}$	<i>Latitude time-derivative</i>
ϵ	<i>Thrust angle 1</i>	LOX	<i>Liquid oxygen</i>
E	<i>Eccentric anomaly</i>	M	<i>Mean anomaly</i>
\mathbf{e}	<i>Eccentricity vector</i>	m	<i>Spacecraft mass</i>
e	<i>Eccentricity</i>	m_0	<i>Initial vehicle mass</i>
F	<i>F Lagrange coefficient</i>	m_f	<i>Final total mass</i>
\dot{F}	<i>Derivative F Lagrange coefficient</i>	\dot{m}_f	<i>Vehicle mass time-derivative</i>

μ	Gravitational parameter of a generic central body	ρ	Density
μ_{\odot}	Gravitational parameter of the Sun	SOI	Sphere of influence radius
μ_{\oplus}	Gravitational parameter of the Earth	σ	Relative position vector
μ_{σ}	Gravitational parameter of Mars	T	Temperature
μ_T	Thrust angle 2	T_h	Thrust at a specific height
\mathbf{n}	Nodal vector	TOF	Time of flight
n	Mean angular motion	T_{trans}	Time of transfer
v_1	Initial true anomaly	tm	Transfer method
v_2	Final true anomaly	\mathbf{v}	Velocity vector
Ω	Longitude of the ascending node	$\dot{\mathbf{v}}$	Velocity time-derivative
ω	Argument of periapsis	v	Velocity vector module
ω_p	Planet angular velocity	V_{bo}	Burnout velocity
P	Pressure	v_e	Exhaust velocity
p	Semi-latus rectum or parameter	V_{esc}	Escape velocity
P_e	Pression at nozzle exit area	$V_{injection}$	Injection velocity
R	Ideal gas constant	V_{dep}	Departure velocity
\mathbf{r}	Position vector	V_{HTA}	Transfer velocity at departure planet
r	Position vector module	V_{HTB}	Transfer velocity at arrival planet
$\dot{\mathbf{r}}$	Position time-derivative	V_{planet}	Planet velocity
r_a	Mean distance of departure planet	V_{sp}	Spacecraft velocity
r_b	Mean distance of arrival planet	V_{∞}	Hyperbolic excess velocity

1 INTRODUCTION

This first section is aimed to establish the aim, the scope, the requirements and the justification of the study.

1.1 AIM

The main objective of this project is to analyse the architecture proposed by the company SpaceX to reach Mars, carrying out an in-depth study of each phase of the interplanetary mission.

Firstly, the target will be to determine the characteristics of each phase, focusing on the numerical study of the manoeuvring, secondly, the simulation of the mission and thirdly, a preliminary study of the re-entry process into Mars surface will be conducted.

1.2 SCOPE

Bibliographic review

- Review and expand the concepts of Astrodynamics, focusing on orbital manoeuvres and interplanetary trajectories.
- Get more familiar with rocket launches, satellite tracking operations and re-entry manoeuvre.
- Aerothermodynamics, read and understand what is behind this term, study the physics that this term entails.
- Programming language in Matlab software will be reinforced (previously learnt) so as to develop the most optimum codes to obtain the required results.

SpaceX Company

- An investigation into the SpaceX company will be carried out, with the objective of justifying their existence and analysing what has led them to get involved in a mission of such magnitude.
- The main motivations to reach Mars will be described in order to understand the risk of get involved into such a great interplanetary mission.

SpaceX Mission Analysis and Synthesis: Starship

- The main objectives of the mission will be analysed, focusing on the requirements of the mission and describing the main milestones that must be met.
- The timeline planned by the company will be raised, and the current situation of the project and the status of the next steps to be carried out will be investigated.
- Mission architecture analysis
 - An investigation will be carried out on the proposed mission architecture, in order to detail all available data as accurately as possible.

- A preliminary analysis of the mission will be carried out, following the method called 'patched-conic-approximation', so as to define the most relevant data and to determine its viability.
- In-depth study of each phase present in the mission, describing what implies and what procedures must be followed in each of them, in addition to get familiar with the different orbits in which the spacecraft is traveling at each moment.
- A numerical study of the manoeuvres that will be done during the mission will be conducted, focusing it on the different Δv applied on each of the mentioned manoeuvres.
- A study will be developed regarding the possible launch windows, with the aim of determining which are the most favourable moments to start the interplanetary journey.
- In order to visualize the manoeuvres that are carried out throughout the mission in a global way, Matlab will be used to plot the different phases trajectories that the interplanetary mission analysed entails.

Dedicated Spacecraft Subsystems Description

- The physical elements used in the mission will be identified, explaining their characteristics and what they contribute to the design of the project.
 - Investigate the different propulsive methods that will be used during the different phases of the interplanetary mission, describe them and specifically define the amount of fuel that can accommodate the spacecraft in total.
 - All the information of the propulsive system of the spacecraft used to take it to its destination will be detailed, analysing the different stages.
 - Description of the new spacecraft designed by the company for this mission, and the possible uses for which it could be destined will be analysed.
 - Identification of the launch area of the Starship, as well as the possible launch zones required for new purposes for it.
 - Description of the manufacturing and assembly area of the Starship.
 - Research on attitude sensors and how to control this magnitude, with the aim of describing the implementation for the Starship spacecraft.
 - Description of the different methods of orbital adjustment along the path followed by Starship during the interplanetary mission.
 - A study will be conducted regarding the possibilities of energy generation along an interplanetary journey, as well as the process of storing the energy.
 - Research on the process of obtaining fuel on the surface of Mars will be carried out – the process will be analysed and described specifically.

Re-entry process into Mars Surface

- The conditions of the atmosphere of Mars will be investigated through documentation, with the aim of proposing a reliable atmospheric model (density as a function of height) of said planet.
- Numerical computation of the aerodynamic characteristics of the Starship will be made once it has entered the atmosphere of Mars.

Architecture proposal study

- In order to demonstrate the utility of the architecture tool developed, it will be proposed a Mars' colonization strategy for then study a concrete period of time, analysing all phases involved.

Mars society competition case study

- As a case study, it will be defined the main materials required for manufacture the necessary shuttles and launchers so as to accomplish the Mars' colonization process proposed by the team that participates in the Mars' society competition. The study is based on the Starship and Super Heavy rocket weight budgets developed, considering the total mass and the fuel mass of each vehicle.

Conclusions and future work

- Future lines of work within the same field will be suggested to go further.

Out of Scope

It is important to note that there are some studies that could be done in the field that this project belongs to, but either because they are not fully focused on the main objective of the project, or due to lack of time, they will not be covered in this thesis.

- Design of the spacecraft subsystems.
- Deep study regarding the attitude sensing and control.
- Deep study regarding the orbital adjustment.
- Thermal analysis of the re-entry process into Mars.
- Investigation regarding the thermal shields.
- Analysis of the different materials implemented in the spacecraft.
- Study of the process of the creation of a Human-Base in Mars.
- Economic feasibility analysis of the mission.
- 3D simulation of the mission in a specific space software.

1.3 REQUIREMENTS

First of all, the specific requirements that must be met to complete the study regarding the content of the project are presented:

- Specific description of each phase of the Starship mission.
- Numerical study of the different orbital manoeuvres performed throughout the mission.
- Description of the sensors and the attitude control of the interplanetary spacecrafts.
- Investigation regarding the orbital adjustment used by interplanetary spacecrafts.
- Preliminary study of the re-entry of Starship on the surface of Mars.
- Simulation of the different trajectories used to reach Mars using Matlab.
- Analysis of the different motivations that lead to Mars and description of the benefits of conducting this journey.
- Justification regarding the architecture choice implemented by the company for the interplanetary manned mission.

To conclude this section, the requirements that must be met in the project regarding the regulations that govern its development are introduced below:

- Invest a total of, at least, 600 hours in the development of the study.
- Develop all the documentation in British English.
- Deliver the project on 30th June, 2020.

1.4 JUSTIFICATION

Mars' exploration has been an objective of the scientific community since the beginning of the 20th century. Proposals range from sending space probes to its orbit, to most ambitious projects such as manned missions to reach the red planet – in this concrete field of investigations is where this thesis is based. SpaceX is an aerospace company which is developing solutions to bring humans to Mars, and, as the ultimate target, to make interplanetary life a reality. The opportunities that arise from achieving these goals are many and very varied, but since it is necessary to invest an enormous amount of resources to successfully carry out these projects, it is essential to analyse them and consider whether they are worthy. Therefore, the main reasons why Mars is the target planet for the near future are exposed below.

On the one hand, the scientific studies that have been proposed are really relevant, as in the beginning it was a warm planet and contained liquid water on its surface for over than 100,000 years, which represents five times the time it took for life to arise on Earth. Thus, if the theory that life is a natural development of some chemical components, that is to say, water and certain elements, during enough time is correct, Mars could have harboured life on its surface at some point in history. Arriving to Mars offer the possibility of founding fossils, which would prove the theory as correct, and that the development of life is a phenomenon that occurs throughout the Universe. Otherwise, if the evidence of water is found but no fossils are encountered, it could indicate that the development of life is not a natural process that occurs with much probability, but rather a process that requires a component of

random, and consequently the probability of finding extraterrestrial life would be reduced. Furthermore, there is even the possibility of finding underground water and discover life at that very moment.

On the other hand, Mars is the closest planet to the Earth, and as far as it is known, it contains the ingredients for life and therefore for civilization. The arrival to Mars could be the beginning of an interplanetary life for human being, establishing first a base on the red planet and, from there, linking it with the establishment of new bases on nearby planets. The achievement of such a dare would encourage people to develop new technologies, allowing to accomplish challenges that currently are reserved for science fiction.

Digging into the history, it is easy to realize that are these achieved milestones those which prevail over news that day to day fill newspapers. For instance, when somebody thinks about year 1492, the first thought is regarding the trip of Christopher Columbus, in which he sailed to America. However, in this year, England and France signed their peace treaty, the Borgias came to the papacy, and Lorenzo de Medici, the richest man in the world in the epoch, died. The news mentioned would be trending topic nowadays, but instead of remembering them, an Italian's journey into the unknown is the feat which is remembered from that time.

2 BACKGROUND

In order to establish the basis of the historical background necessary to understand the reasons for carrying out the study presented in this thesis, in this section it is exposed firstly the theoretical framework needed to develop the analysis developed during the project, secondly the state of the art of the space missions, whether they are interplanetary or not, and thirdly the analysis regarding the SpaceX company is detailed, focusing it on its foundation, as well as on the projects executed under the SpaceX brand.

2.1 STATE OF THE ART

Space exploration is a matter that has aroused interest in humans since the dawn of time – citing great scientific researchers of the past ‘exploring space is an intrinsic interest in the human being’. The motivations that drive such research are very diverse, from discovering what position the Earth occupies within the infinite universe to seeking extraterrestrial life.

Throughout recent history, great advances have been made in terms of space research [3]. The first artificial satellite was launched by the former Soviet Union in 1957, called *Sputnik-1*, beginning a new space adventure whose culminating moment was undoubtedly the arrival to the Moon in the *Apollo 11* mission, in 1969. Since then, many space experiments have been developed and launched into orbit from Earth; These include the *Mir Space Station*, belonging to the Soviet Union, the launch of the *Hubble Space Telescope* or the *International Space Station* – a mission in which five renowned space agencies joined forces, and which involved a common international project to big scale.

So far, interplanetary trips have been carried out without a crew, which greatly simplifies the mission since it is not necessary to implement an interplanetary cruise habitat in which human life is sustainable. It should be noted that the cosmic radiation to which spacecrafts are subjected along their trajectory is a magnitude to be taken into account, which makes even more difficult sending human beings on space travel. Among the probes sent to other planets are *Cassini* and *Huygens*, both sent to Saturn, and the *Stardust* probe, sent to the meeting of comet *P/Wild 2*.

The trip that most closely resembles the mission analysed in this project is the one conducted successfully by NASA with the *Apollo* program (through which it was possible to land on the lunar surface and return to Earth), because those were manned space travel projects. Specifically, in the *Apollo 11* mission, a trajectory called Lunar Orbit Rendezvous (LOR) was used, in which a large spacecraft travels along with a smaller module (in this case the lunar module) until reaching a concrete Moon orbit. Once at this point, the main spacecraft remains in orbit while the lunar module descends to the surface of the natural satellite. Once the operations on the lunar surface are completed, the module ascends to the orbit in which the main spacecraft is orbiting in order to perform the rendezvous and re-docking manoeuvre.

It should be mentioned that in this project it is necessary to conduct an exhaustive process of research in various subjects, code programming to obtain relevant numerical results in regard to the space mission studied and relevant acquisition of knowledge in orbital simulation. Hence, it is a must to verify the sources of research, to validate the codes developed and to render the simulation of the trajectories optimally.

To conclude this brief description of space history, it is necessary to highlight the main missions carried out so far on the surface of Mars. In the early sixties the first attempts to reach the red planet began, but it was not until 1965 when the United States managed to capture images of Mars and transmit them to Earth, with *Mariner 4*. Nevertheless, the first object landed and controlled from Earth on the martian surface was operated by the Soviet Union, in 1971 with *Mars 3*. In 1997 the first rover, called *Sojourner*, was landed in Mars surface, which carried out a two-month mission exploring the planet. In 2001 the existence of ice on the red planet was confirmed, through the *Mars Odyssey* mission. This discovery led to a boom in Mars exploration, accumulating a total of six space instruments on this planet in 2008. In 2011, the *Mars Science Laboratory* was launched, with the aim of analysing samples of soil and rock dust present in the Mars surface.

Until then, the main motivation of the missions to Mars was to discover whether this planet was or had been habitable at some point in its history. Today, motivation has changed. The investigations move towards building a habitable martian base, and therefore the biggest challenge is to solve the transport method for all the payload that will be necessary to develop this base, as well as the transport method for the humans that will live there.

Looking ahead, there are many open fronts, and in this academic project is conducted an analytical study of the mission architecture proposed by SpaceX, perhaps the most ambitious of the existing ones, with the aim of bringing the human being one step closer to realizing the dream of a multiplanetary life.

2.2 THEORETICAL FRAMEWORK

In this subsection, the basic formulae required to establish the basis of the numerical study of the architecture mission are described. Kepler's Laws of orbital dynamics are first mentioned, and also the orbital parameters, followed by the explanation of the basic orbital manoeuvres, the Lambert problem and the method called Patched Conic Approximation. Finally, the equations used for the ascent and entry studies are presented.

2.2.1 Fundamentals of Astrodynamics

The three laws which govern the celestial bodies motion which orbit any central body are listed below:

1. Every planet moves in an elliptical orbit, with the central body at one focus of the ellipse.
2. The radius vector drawn from the central body to any planet sweeps out equal areas in equal times.
3. The squares of the periods of revolution of the planets are proportional to the cubes of the semi-major axis of their orbits.

These three laws are known as the Keplerian laws and can be derived by considering a two-body problem – it was first solved by Sir Isaac Newton. As the algebraic proof of the Keplerian laws can be found in various textbooks, as in reference [7], and therefore it is not presented in this text.

The position of any object in orbit is defined by using six orbital parameters, which are also known as the Keplerian elements. A description of each orbital parameter is presented below, together with an image that schematically presents the angular orbital parameters, in Figure 1, so as to facilitate their understanding.

Eccentricity: It is the parameter which determines the shape of the orbit, and it is a property of the conic section that allows to differentiate them. For a circle the eccentricity is equal to zero, for an ellipse is less than one, for a parabola is equal to one and for a hyperbola is higher than one.

Semi-major axis: It is defined as the half of the sum of the apoapsis and the periapsis of an orbit with eccentricity less than one. If the eccentricity is equal to one, the semi-major axis tends to infinity, and if it is greater than one the semi-major axis has negative value.

True anomaly: It is an angular parameter which defines the position of a body moving along its orbit. It quantifies the angle between the direction of periapsis and the current position of the body, seen from the main focus of the ellipse, where the central body is allocated. It ranges from 0 to 2π .

Inclination: It is an angular parameter which measures the angle between a reference plane and the orbital plane through which the body is moving. It ranges from 0 to π .

Longitude of the ascending node: It is an angular parameter which measures the angle from a determined reference direction, named as the origin of longitude, to the direction of the ascending node, measured in a specified reference plane. It ranges from 0 to 2π .

Argument of perigee: It is an angular parameter which measures the angle between the body orbit plane that is measured from the ascending node to the perigee point along the body's direction of movement. It ranges from 0 to π .

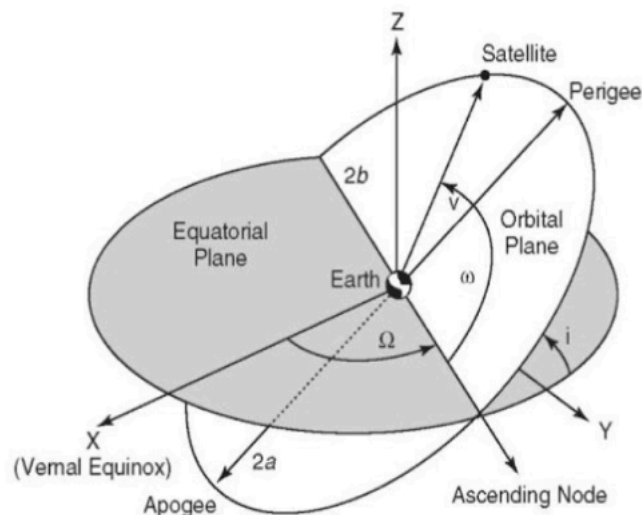


Figure 1. Orbital elements of a Keplerian orbit [20]

In order to define the different Keplerian orbits, it is presented in Table 1 their main properties.

Table 1. Main properties of the conic sections

Conic Section	Eccentricity	Semi-major axis	Energy
Circle	0	= radius	< 0
Ellipse	$0 < e < 1$	> 0	< 0
Parabola	1	infinity	0
Hyperbola	> 1	< 0	> 0

2.2.2 Basic orbital manoeuvres

An orbital manoeuvre is the act of modifying the orbital parameters of a body which is orbiting around a central body. The changes produced on these orbital elements are due to variations in magnitude or in direction of the orbital velocity of the body. In order to simplify the manoeuvring study, the orbital velocity changes are always considered as impulse velocity changes, and it can be assumed to be a realistic approximation as in most of the current propulsion systems the orbital period is much larger than the propulsion period. Depending on the concrete requirements of the phase mission, there are various types of orbital manoeuvres, such as coplanar or non-coplanar transfer, bi-elliptic transfer and so on. In this case, the most efficient in with respect to energy efficiency is described, i.e. Hohmann transfer, as it is used in the preliminary mission analysis.

Hohmann transfer

Walter Hohmann first suggested the most energy efficient orbital transfer, in 1925. In this theory, it is proposed that the minimum change in velocity for transfer a body from an initial circular orbit to a destination circular orbit could be achieved by using two tangential burns. It is important to point out that both circular orbits must be coplanar [7]. Therefore, in a Hohmann transfer there are two burns, the first at the initial departure orbit with a flight path angle of 0 and the second one at the arrival orbit with a flight path angle of π radians. Therefore, in this theory there are not considered neither parabolic orbits nor hyperbolic orbits, and the transfer orbit is represented as an ellipse, which is usually named transfer ellipse.

The departure position is the perigee of the transfer ellipse, and the arrival point is its apogee. Thus, the semi-major axis is easily defined.

$$a_{HT} = \frac{r_A + r_B}{2} \quad (2.1)$$

Then, the time of transfer is determined as half of the total period of an ellipse.

$$T_{trans} = \pi \sqrt{\frac{a_{HT}^3}{\mu_{\odot}}} \quad (2.2)$$

In Figure 2 is presented the basic Hohmann transfer between two circular orbits.

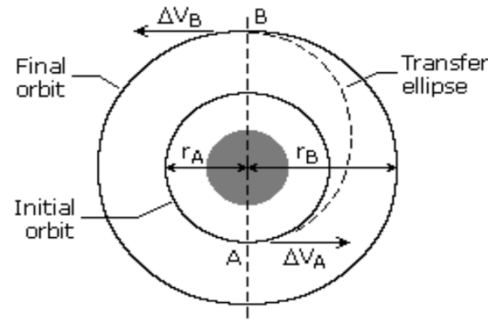


Figure 2. Basic Hohmann transfer [20]

For solving a Hohmann transfer between two coplanar circular orbits as presented in the previous figure, the next numerical process can be followed:

First, the orbital velocities at initial and final orbit are calculated.

$$V_A = \sqrt{\frac{\mu_{\oplus}}{r_A}} \quad (2.3)$$

$$V_B = \sqrt{\frac{\mu_{\oplus}}{r_B}} \quad (2.4)$$

Then, the velocity needed for start the transfer ellipse and the velocity needed to stay at the final orbit are obtained, starting from the vis-viva equation.

$$\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \quad (2.5)$$

Solving the vis-viva equation for the velocity, the velocities of the transfer at point A and point B are calculated.

$$V_{HTA} = \sqrt{\mu_{\odot} \left(\frac{2}{r_A} - \frac{1}{a_{HT}} \right)} \quad (2.6)$$

$$V_{HTB} = \sqrt{\mu_{\odot} \left(\frac{2}{r_B} - \frac{1}{a_{HT}} \right)} \quad (2.7)$$

Now, it is possible to obtain the first and second velocity changes, and finally the total ΔV required for conducting the transfer.

$$\Delta V_A = V_{HT_A} - V_A \quad (2.8)$$

$$\Delta V_B = V_{HT_B} - V_B \quad (2.9)$$

$$\Delta V_{tot} = \Delta V_A + \Delta V_B \quad (2.10)$$

As it can be seen from the equations defined above, there are two important considerations which have been done so as to develop this study: on the one hand, the gravitational attraction of the other bodies which are near the element that performs the transfer has been ignored, and on the other hand, the planetary orbits are not circular, and therefore the Hohmann transfer can be used just as a preliminary approximation for an interplanetary transfer. These assumptions will be discussed in subsection 3.3.1, where a Hohmann transfer is used for a preliminary mission analysis.

2.2.3 Orbit determination and trajectory computation

A trajectory is defined as the path described by any moving object as a function of time. An object moving in a potential field traces a path and it can be described by using differential equations. As the initial values are obtained from observation or defined by the user, the differential equations can be integrated so as to obtain the complete trajectory [10].

Lambert problem

One way of determining the orbit of a body travelling in space is by defining the initial and the final position, and a time of flight for covering the route. In addition, it is important to determine if it is desired to travel from the starting point to the end using a Type I or Type II trajectory. As it is known, there are infinite possible orbits to go from starting point to final point, but as a concrete time of flight has been determined as a requirement, the number of possible trajectories is restricted to two, differentiated by the value of true anomaly – being Type I the trajectories with true anomaly less than π and Type II being the trajectories with true anomaly greater than π . In Figure 3 it is represented both possible trajectories. This problem is known as the Lambert Problem, also known as the orbital boundary value problem. In order to obtain the main results of the numerical analysis conducted in this thesis for the interplanetary transfer between the Earth and Mars, the method used for solving the Lambert problem has been built using a Newton-Raphson iterative strategy, along with the implementation of a continuation method and a differential corrector. It includes the use of Lagrange coefficients, as well as a preliminary estimate of the minimum transfer energy between two points in space. The previously mentioned techniques implemented to solve it are briefly described below.

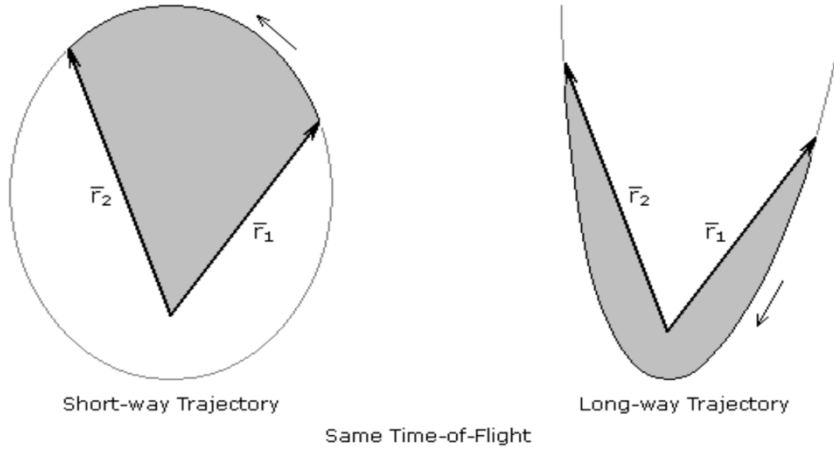


Figure 3. Type I and Type II trajectories [7]

Lagrange Coefficients

The Lagrange Coefficients are used in several steps of the Lambert solver structure, in order to obtain the solution to the orbital motion in each situation analysed. There are defined below.

First of all, it is needed to define as the true anomaly difference $\Delta v = v_2 - v_1$, and:

$$e \cos v_1 = \frac{p}{r_1} - 1 \quad (2.11)$$

$$e \sin v_1 = \frac{\sqrt{p}}{r_1} \sigma_1, \text{ where } \sigma_1 = \frac{r_1 \cdot v_1}{\sqrt{\mu}} \quad (2.12)$$

$$r(\Delta v) = \frac{pr_1}{r_1 + (p - r_1) \cos \Delta v - \sqrt{p} \sigma_1 \sin \Delta v} \quad (2.13)$$

Then, the Lagrange coefficients can be expressed in the following notation:

$$F = 1 - \frac{r}{p} (1 - \cos \Delta v) \quad (2.14)$$

$$G = \frac{rr_1}{\sqrt{\mu p}} \sin \Delta v \quad (2.15)$$

$$\dot{F} = \frac{\sqrt{\mu}}{r_1 p} [\sigma_1 (1 - \cos \Delta v) - \sqrt{p} \sin \Delta v] \quad (2.16)$$

$$\dot{G} = 1 - \frac{r_1}{p} (1 - \cos \Delta v) \quad (2.17)$$

Newton-Raphson iterative strategy

Kepler's equation relates time and position along an orbit. It is presented here below the Kepler's equation for an ellipse:

$$M(t) = n(t - t_{periapsis}) = E - e \cdot \sin E = M(E) \quad (2.18)$$

Where E is the eccentric anomaly, M is the mean anomaly and

$$n = \sqrt{\frac{\mu}{a^3}} \quad (2.19)$$

$$a = \frac{\mu}{\frac{2\mu}{r} - v^2} \quad (2.20)$$

$$r_{periapsis} = a(1 - e) \quad (2.21)$$

In order to obtain the position at a certain time t it is possible to use a Newton-Raphson iterative strategy. It represents an iterative, gradient-based approach to find the root of a function.

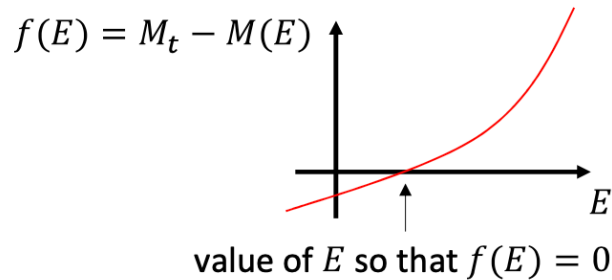


Figure 4. Newton-Raphson illustration [10]

Based on an initial guess of the solution E_k a new guess is obtained through the derivative function $f(E)$. Previously to the iterative process, it is necessary to set up a tolerance, which will determine whether the difference between the obtained value and the desired value is enough for considering the result as valid; i.e. $|f(E_k + 1)| < \epsilon$, where ϵ is the tolerance.

Differential corrector

So as to obtain the required velocity change for achieving a desired change in position, once a certain initial position and initial velocity has been provided, it is useful to implement a differential corrector.

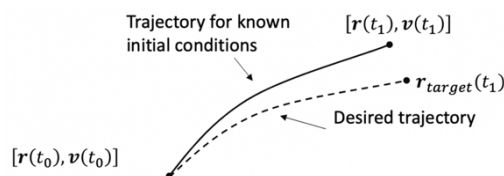


Figure 5. Trajectory iterative illustration [10]

The equations of motion along the reference trajectory are $f(x_{ref}(t), t)$, presented below.

$$f(x(t), t) = \dot{x}(t) = \begin{cases} \dot{x} = v_x \\ \dot{y} = v_y \\ \dot{z} = v_z \\ \dot{v}_x = -\frac{\mu}{r^3}x \\ \dot{v}_y = -\frac{\mu}{r^3}y \\ \dot{v}_z = -\frac{\mu}{r^3}z \end{cases} \quad (2.22)$$

On the other hand, the equations of motion of the desired trajectory are $f_{des} = f(x_{ref} + \delta x(t), t)$. The function f_{des} can be linearly approximated through a first-order Taylor expansion:

$$f_{des} = \dot{x}_{des}(t) = \dot{x}_{ref}(t) + \delta \dot{x}(t) \approx f(x_{ref}(t), t) + \frac{\delta f(x_{ref}(t), t)}{\delta x(t)} \delta x(t) \quad (2.23)$$

Where the term $\frac{\delta f(x_{ref}(t), t)}{\delta x(t)}$ represents a Jacobian matrix, formed by partial derivatives of the equations of motion with respect to a state vector. The vector δx is named as deviation vector, and its evolution over time is relevant for achieving the desired final trajectory. It can be approximated as:

$$\delta \dot{x}(t) \approx \frac{\delta f(x_{ref}(t), t)}{\delta x(t)} \cdot \delta x(t) \quad (2.24)$$

Now, a general solution to a linear system of ordinary differential equations (ODE) can be constructed, starting from a combination of independent linear solutions:

$$\delta x(t) = \Phi(t, t_0) \cdot \delta x(t_0) \quad (2.25)$$

Therefore, it is obtained an expression for the deviation from the reference trajectory along time $\delta x(t)$ as a function of the initial deviation $\delta x(t_0)$. The matrix relating these two quantities is denominated as state-transition matrix (named as $\Phi(t, t_0)$). If the main goal is to obtain the required change in initial conditions to achieve a desired state at time t_1 , it is needed to invert the previous equation:

$$\delta x(t_0) = \Phi(t, t_0)^{-1} \cdot \delta x(t_1) \quad (2.26)$$

Thus, it is necessary to know matrix $\Phi(t, t_0)$, that can be numerically integrated from time t_0 to time t_1 along with the reference trajectory. However, since the Lambert problem is being solved considering a patched conic approximation (described later), three different two-body problems are being considered, and for this type of exercises there is an analytical solution for the state-transition matrix,

and it is not needed to compute numerically the derivatives. In particular, the block Φ_{rv} of the state-transition matrix, which is the required for obtaining the initial velocity needed to achieve a desired final position, can be computed as:

$$\frac{\partial \mathbf{r}(t_f)}{\partial \mathbf{v}(t_0)} = \Phi_{rv} = \frac{\partial \mathbf{r}_f}{\partial \dot{\mathbf{r}}_0} = \frac{r_0}{\mu} (1 - F)(\Delta \mathbf{r} \cdot \dot{\mathbf{r}}_0^T - \Delta \mathbf{v} \cdot \dot{\mathbf{r}}_0^T) + \frac{C}{\mu} \dot{\mathbf{r}}_f \cdot \dot{\mathbf{r}}_0^T + G \cdot I_{3 \times 3} \quad (2.27)$$

The definition of the parameters involved in previous equation are presented here below:

$$\Delta \mathbf{r} = \mathbf{r}_f - \mathbf{r}_0 ; \Delta \mathbf{v} = \dot{\mathbf{r}}_f - \dot{\mathbf{r}}_0 \quad (2.28)$$

$$\dot{G} = 1 - \frac{a}{r_f} (1 - \cos \Delta E) \quad (2.29)$$

$$\dot{\mathbf{r}}_f = \frac{1}{G} (\dot{G} \mathbf{r}_f - \mathbf{r}_0) \quad (2.30)$$

$$C = a \sqrt{\frac{a^3}{\mu}} (3 \sin \Delta E - (2 + \cos \Delta E) \Delta E) - a \Delta t (1 - \cos \Delta E) \quad (2.31)$$

Continuation method

In order to obtain the solution of an iterative problem, a continuation method is used when it is necessary to estimate an initial guess, which is far away from the solution of the said problem. This method represents an approach to obtain intermediate solutions, increasingly closer to the desired one. It is presented below as an example the general equation that follows a specific parameter applying the continuation method.

$$A_k = \lambda_k \cdot A_{desired} + (1 - \lambda_k) \cdot A_{initial} \begin{cases} \lambda_k = \frac{k}{N} \\ k \equiv \text{current iteration} \\ N \equiv \text{total number of iterations} \end{cases} \quad (2.32)$$

It is used for improving the robustness of the algorithm. Combining it with the previously described Newton-Raphson iterative strategy and the differential corrector, it is solved the Lambert problem. It is important to note that the necessary inputs are the starting and the ending position, a certain time of flight, a value that determines whether it is desired to travel the long or short trajectory and finally the gravitational parameter of the central body. Subsection 3.3.3 describes the code structure in detail.

2.2.4 Orbital elements obtainment

Once the Lambert problem has been solved and the position and velocity vectors are obtained in the central body's equatorial frame, the Keplerian elements of the body can be obtained [19].

First it is obtained the specific angular momentum \mathbf{h} , which is perpendicular to the orbital plane.

$$\mathbf{h} = \mathbf{r} \times \mathbf{v} \quad (2.33)$$

Then, the nodal vector \mathbf{n} is calculated, which is perpendicular to both the orbital plane and the central body's equatorial plane, and it has to lie in the line of nodes (the intersection between both planes mentioned before).

$$\mathbf{n} = \mathbf{z} \times \mathbf{h} \quad (2.34)$$

The eccentricity vector is obtained using the next equation, and it points from the focus toward perihelion with a magnitude equal to the eccentricity of the orbit.

$$\mathbf{e} = \frac{1}{\mu} \left[\left(v^2 - \frac{\mu}{r} \right) \mathbf{r} - (\mathbf{r} \cdot \mathbf{v}) \mathbf{v} \right] \quad (2.35)$$

The semimajor axis is obtained from the vis-viva equation.

$$a = \frac{2}{\mu} \left(\frac{\mu}{r} - \frac{v^2}{2} \right) \quad (2.36)$$

The inclination of the orbit is the angle between \mathbf{z} and \mathbf{h} .

$$\cos i = \frac{h_z}{h} \quad (2.37)$$

The longitude of the ascending node is the angle between \mathbf{x} and \mathbf{n} , and it ranges from 0 to 2π ; therefore, the correct quadrant has to be assigned. If n_y is a positive value, the longitude of the ascending node is less than π .

$$\cos \Omega = \frac{n_x}{n} \quad (2.38)$$

The argument of periapsis is the angle between the nodal vector and the eccentricity vector, and if e_z is a positive value, ω is less than π .

$$\cos \omega = \frac{(\mathbf{n} \cdot \mathbf{e})}{n e} \quad (2.39)$$

Finally, the true anomaly is obtained, and is less than π when $\mathbf{r} \cdot \mathbf{v}$ is a positive value.

$$\cos v = \frac{(\mathbf{e} \cdot \mathbf{r})}{e r} \quad (2.40)$$

2.2.5 Patched Conic Approximation

The Patched Conic Approximation (PCA) is a solver used for obtaining good approximation of trajectories for interplanetary spacecraft missions. It represents a reduction in the difficulty level of the study, since with its use, the initial n-body problem is reduced to several two-body problems, for which the solutions are the conic sections of the Keplerian orbits [12]. This simplification is achieved by dividing space into various zones, assigning each body involved in the transfer its own sphere of influence.

From Newton's laws it is known that the gravitational force of attraction is inversely proportional to the square of distance between the centre of the two bodies. Thus, it is possible to assume that when a body is close enough to one central body compared to the other bodies, the forces of attraction to which the orbiting body is subjected to is caused only by the nearby body, thus neglecting the effect caused by the other celestial bodies. It is named as sphere of influence the three-dimensional zone with radius equal to the distance at which the influence of other bodies can be neglected, defined as follows:

$$SOI = a \left(\frac{m}{M} \right)^{\frac{2}{5}} \quad (2.41)$$

Where a is the semi-major axis, m is the mass of the spacecraft and M is the mass of the central body. Therefore, when the spacecraft goes through the sphere of influence of any of the celestial bodies, it is only affected by the gravitational field created by this particular body, neglecting the effect caused by the rest of the bodies in the universe. In this case, the study is divided in three phases:

1. Departure from Earth → The spacecraft is inside the Earth SOI
2. Interplanetary trajectory → The spacecraft is inside of the Sun SOI
3. Arrival to Mars → The spacecraft is inside of the Mars SOI

For phases 1 and 3 the spacecraft describes a hyperbolic trajectory, and in phase 2 it describes an elliptical trajectory around the Sun, in which Lambert problem is solved (following the previous explanation). Finally, the three sections must be patched, and even though splitting the trajectory into different phases entails some errors in the calculations, the PCA gives a good approximation for the spacecraft path and enables the first iteration of the total ΔV budget calculation. In Figure 6 it is presented schematically the PCA transfer.

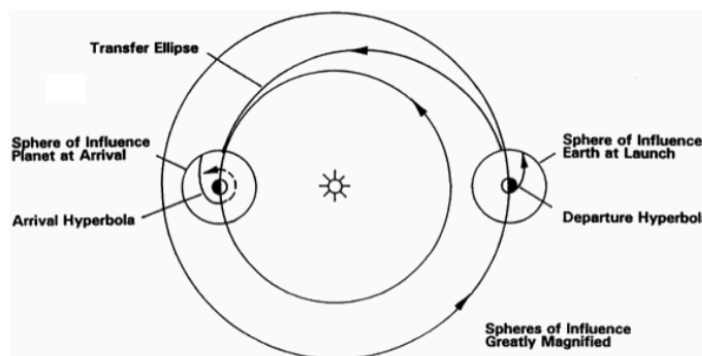


Figure 6. Patched Conic Approximation transfer representation [12]

Hyperbolic departure

A spacecraft which has been designed for interplanetary missions needs to overcome the escape velocity of the Earth, and once this is achieved, it is in a non-closed conic orbit, typically a hyperbolic orbit.

In Figure 7 is presented an illustration of the hyperbolic departure.

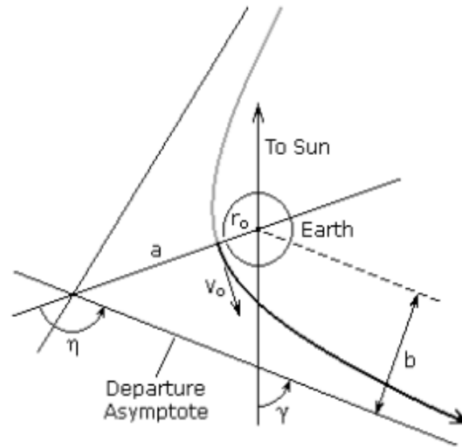


Figure 7. Hyperbolic departure trajectory illustration [12]

The departure velocity obtained from the Lambert solver is relative to the central body (Sun in case of an Earth-Mars transfer). Therefore, the first step is to calculate the relative velocity of the spacecraft with respect to the planet.

$$V_{sp} = |\mathbf{V}_{dep} - \mathbf{V}_{planet}| = \sqrt{V_{sp_x}^2 + V_{sp_y}^2 + V_{sp_z}^2} \quad (2.42)$$

If the spacecraft velocity is equal to the escape velocity, it leaves the central body in a parabolic path, but if the velocity change is greater, it leaves the central body in a hyperbolic path, as there is a velocity component greater than zero at infinity. If the burnout velocity is V_{bo} , the velocity at infinite is obtained from:

$$V_{\infty}^2 = V_{bo}^2 - V_{esc}^2 \quad (2.43)$$

It is important to remark that the velocity at the infinite should be understood as the velocity that has the spacecraft when escapes from the sphere of influence of the central body. It is possible to assume that V_{sp} obtained from Lambert solver is equal to the infinite velocity. Being r the departure planet radius, the injection velocity from the surface of the Earth can be obtained from the equation presented below.

$$V_{injection} = \sqrt{V_{\infty}^2 + \frac{2\mu}{r}} \quad (2.44)$$

Now, considering that the initial state of the hyperbolic trajectory is a circular parking orbit around the central body, the required ΔV can be obtained from next equation, where r_p is the distance of the perigee altitude of the initial parking orbit.

$$\Delta V = V_{injection} - \sqrt{\frac{\mu}{r_p}} \quad (2.45)$$

An important parameter that can be obtained is the zenith angle, which represents the angle between the radius of the trajectory and the departure asymptote. It can be obtained from next equation.

$$\gamma = \arccos\left(\frac{r_x v_x + r_y v_y + r_z v_z}{r v}\right) \quad (2.46)$$

Hyperbolic arrival

The spacecraft velocity obtained from the Lambert solver is always hyperbolic relative to the destination. As the Lambert problem is solved for a certain time of flight and assuming a concrete final position vector, the entry is always an impact at the centre of the target planet. However, if the mission requires the object to arrive at a miss distance to the target planet, it has to be conducted an extra study. In the case of this thesis, the architecture analysed considers a direct entry to the target planet, and therefore it is not described the process necessary to stay in an orbit prior to entering the target planet. It is important to remark that the assumptions conducted for the hyperbolic departure are also considered in the hyperbolic arrival; i.e. the infinity velocity is equal to the velocity of the spacecraft obtained from the Lambert solver, and the velocity just before entering the Mars SOI is equal to the velocity just after entering it. In this way, the continuity and differentiability are maintained in the interplanetary transfer at both points of discontinuity, ensuring that all trajectories are patched.

2.2.6 Ascent and entry study

There is a very important difference between the studies described above and the study that follows: in the previous studies, the spacecraft is traveling in space, and in both the ascent and the entry studies, the spacecraft travels in the an atmosphere, either on the departure or the target planet atmosphere. Therefore, it is really important to consider the aerodynamic effects. In this thesis, both the ascent and the entry study are considered, and here below are presented the cinematic and dynamic equations used for conducting both analyses [25].

The kinematic equations are defined next, defining the time derivatives of the position, the latitude and the longitude.

$$\dot{r} = v \sin \phi \quad (2.47)$$

$$\dot{\delta} = \frac{v}{r} \cos \phi \cos A \quad (2.48)$$

$$\dot{\lambda} = \frac{v \cos \phi \sin A}{r \cos \delta} \quad (2.49)$$

As for the dynamic equations, they are presented below, defining the time derivatives of the velocity, the azimuth angle and the flight path angle.

$$m\dot{v} = f_T \cos \epsilon \cos \mu_T - D - mg_c \sin \phi + mg_\delta \cos \phi \cos A - m\omega^2 r \cos \delta (\cos \phi \cos A \sin \delta - \sin \phi \cos \delta) \quad (2.50)$$

$$mv \cos \phi \dot{A} = m \frac{v^2}{r} \cos^2 \phi \sin A \tan \delta + f_T \sin \mu_T + f_Y - mg_\delta \sin A + m\omega^2 r \sin A \sin \delta \cos \delta - 2m\omega v (\sin \phi \cos A \cos \delta - \cos \phi \sin \delta) \quad (2.51)$$

$$mv\dot{\phi} = m \frac{v^2}{r} \cos \phi + f_T \sin \epsilon \cos \mu_T + L - mg_c \cos \phi - mg_\delta \sin \phi \cos A + m\omega^2 r \cos \delta (\sin \phi \cos A \sin \delta + \cos \phi \cos \delta) + 2m\omega v \sin A \cos \delta \quad (2.52)$$

2.2.7 Tsiolkovsky equation

In order to estimate the required fuel for conducting several manoeuvres, it is used the Tsiolkovsky equation, derived below [22].

If no force is acting on the spacecraft while it is moving in vacuum (i.e. null environmental pressure), conservation of linear momentum states:

$$(m + \Delta m_f)v = m(v + \Delta v) - \Delta m_f(v_e - v) \Rightarrow m\Delta v = \Delta m_f v_e \quad (2.53)$$

Where Δm_f is the burnt propellant ejected through the rocket nozzle at exhaust velocity (v_e , relative to the vehicle). By converting the finite-variations terms into derivative-terms, it can be obtained:

$$m \frac{dv}{dt} = \dot{m}_f v_e + p_e A_e \quad (2.54)$$

Where the time-derivative of the vehicle mass is equal to the time-derivative of the spacecraft mass but of opposite sign (i.e. $\dot{m} = -\dot{m}_f$), and the additional term $p_e A_e$ is due to the difference between p_e at the nozzle exit section area A_e and the environmental pressure p_A . The total thrust provided by the engines can be expressed as:

$$T = p_e A_e + \dot{m}_f v_e = \dot{m}_f c = \dot{m}_f g_0 I_{SP} \quad (2.55)$$

Where c is the effective exhaust velocity, g_0 is the nominal gravity acceleration of the planet surface and I_{SP} is the specific impulse of the rocket. From the equations expressed before, the acceleration can be expressed as:

$$\frac{dv}{dt} = -\dot{m} \frac{c}{m} = -\frac{c}{m} \frac{dm}{dt} \quad (2.56)$$

Which can be integrated by variable separation from the initial condition $v=v_0$ and $m=m_0$, yielding the Tsiolkovsky equation:

$$\Delta v = c \ln \frac{m_0}{m_f} \quad (2.57)$$

Where m_0 is the initial total mass (including the propellant), m_f is the final total mass (once the required propellant has been burnt), Δv is the velocity impulse and c is again the effective exhaust velocity ($c = g_0 I_{SP}$).

2.3 SPACEX COMPANY

SpaceX is a private American aerospace company focused on the design, manufacture and launching of advanced rockets and spacecraft. It was founded in 2002 by Elon Musk, its actual CEO, with the main goal of reducing the space transportation costs in order to enable the colonization of the Universe, starting by Mars [1].

It is headquartered in Hawthorne, California, and currently has more than 6,000 employees. It is important to remark that the majority of its employees are from United States, as the government regulates rocket technology as an advanced weapon technology, making it difficult to hire people born outside the country.

Since its foundation, SpaceX has been gaining worldwide recognition through achieving milestones of high importance in the aerospace world. It is the only private company capable of performing the reentry maneuver of a spacecraft from Low Earth Orbit, achieving this goal for the first time in 2010. Again, in 2012, the focus was on this company when its spacecraft named as Dragon became the leading commercial spacecraft to deliver cargo to and from the International Space Station. In 2017, they achieved the first reflight of an orbital class rocket, and one year later began launching Falcon Heavy, the world's most powerful operational rocket. In order to reduce the space transportation costs, which represents one of the main goals that motivated the creation of the Company, SpaceX has successfully developed a reusable launching system. The technology was developed and initially used for the first stage of Falcon 9, and it is important to highlight that the development of a second stage reuse system is considered paramount to SpaceX's plans to enable the settlement of Mars, but nowadays the investigation regarding this system has been abandoned for the moment.

SpaceX is one of the world's fastest growing providers of launch services, and has over 100 launches on its manifest, representing about \$12 billion in contract revenue. These contracts included both commercial and government (NASA/DOD) customers. In the table presented below, some of the main

contracts that NASA has assigned to the SpaceX company throughout its history, as well as the description of the main objective of each of them and the total investment made can be seen.

Table 2. SpaceX contracts assigned by NASA

NASA contract	Main objective of the mission	Million dollars invested in SpaceX
COTS (2006)	Development of the Dragon and Cygnus cargo spaceships (and also the launchers)	396
CRS 1 (2008)	12 Dragon spaceship missions and 8 Cygnus spaceship missions to the ISS	1,600
CCiCAP (2012)	Development of manned spaceships (Starliner, Dragon V2 and Dream Chaser)	440
CCtCap (2014)	Final phase of development of Dragon V2 and CST-100 Starliner	2,600
CRS 1E (2015)	Additional cargo spaceship missions to the ISS in the period 2017 - 2018	1,200
CRS 2 (2016)	Six additional cargo spaceship missions to the ISS in the period 2019 - 2024	900
Total investment		7,136

Building on what has been achieved through the successful projects of Falcon 9 and Falcon Heavy, and, since it has the financial support of the government, as reinforced by the data presented in Table 2, the company is currently working on a next generation of fully reusable launch vehicles that will be capable of carrying humans to Mars and other destinations in the solar system.

3 SPACEX MISSION ANALYSIS AND SYNTHESIS

This section is addressed to obtain a concrete perspective of the mission phases, focusing the study in the requirements of each of them considering all the available data. First, the main goals of the Starship project will be defined, describing the activities which are planned by the company for the future once the transport method has been established. After that, the timeline planned for the program will be exposed, highlighting the current situation of it and analysing which are the next steps. Finally, the numerical tool developed so as to analyse the mission architecture will be presented, describing all the structure and operation of the codes. As for the results obtained from the tool, they will be presented in section 4, in which it is used for analysing a proposal for the SpaceX project for creating a Martian city, following the timeline mentioned.

3.1 KEY MISSION GOALS

While the intention in the Apollo program was to stay in the Moon surface for short stays, with the Starship project SpaceX aims to make Mars a permanent home for humans. In order to achieve this objective, it is needed to lay the groundwork for the astronauts that in the future will colonize the planet. Therefore, as the plans of the company are very ambitious in the long term, it is important to consider first the most important goals which have to be accomplished so as to successfully advance the mission [4].

Before the astronauts ever set foot on the surface of Mars, they will need to have the essentials, like water and power already set up before they get there. SpaceX plans to send two Starship spacecraft on uncrewed missions, carrying important equipment such as a large array of solar panels and a mining system. This mining system will be the basis of SpaceX's automated propellant production plant, which the company aims to expand in every new mission headed to Mars. This plant will process the large supplies of carbon dioxide and water found on Mars, by using the Sabatier process – in section 5.6 (Fuel generation on Mars surface) the fuel obtainment process will be described.

Once this mission has been successfully completed, the foundations for a Mars colony will have been settled, and SpaceX will be on course for sending the first humans to Mars. The next step will consist of sending two cargo and two crewed Starship spacecraft, carrying about six to eight astronauts each. It is important to remark that astronauts could be staying on Mars anywhere between a few months or a couple of years, depending on the status of the propellant production plant development, as well as on the status of the planned research activities.

One of the most important things the astronauts will have to do when they arrive is setting up a base, and it is unclear yet how the first Martian base will look like. Although many have suggested that it should have a similar design to the International Space Station, with compact pressurized modules, allowing room for expansion, and others have suggested that the initial base on Mars should be built underground, so as to protect the astronauts from the intense radiation and extreme weather experienced on Mars, SpaceX aims to build an entire city, starting with the formation of the aforementioned base, until a completely self-sustainable system is formed, that allows life on the red planet. In Figure 8 can be seen the images that the company itself has made public in one of its presentations about the project.

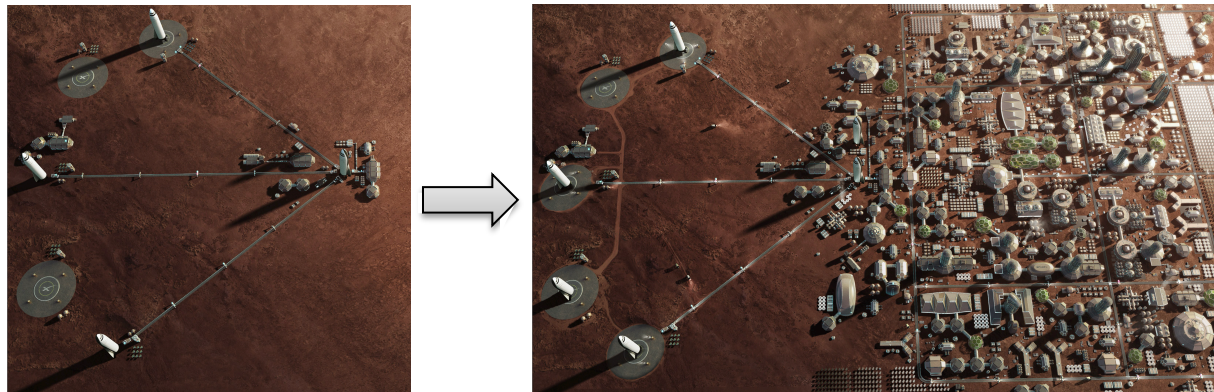


Figure 8. Evolution of the SpaceX concept of the Martian city [11]

Then there is the question of how astronauts will get their food. The company plans to send the first astronauts to Mars with a two-year supply of vacuum sealed packets of food, which are light and compact, just like the ones used on the ISS. The astronauts will not be relying on Mars grown food; however, it is likely that they will bring a greenhouse on their first mission to experiment with growing food and possibly supplementing their food with freshly grown produce.

In order to navigate the surface of Mars, the astronauts will also need a vehicle that can deal with the roughest of terrains. NASA have been developing the ‘Space Exploration Vehicle’ for this exact purpose. This is a pressurized vehicle which can support up to four astronauts for 72 hours. With multiple SEV’s on the surface of Mars, it would allow astronauts to travel more than 200 kilometres in any direction, a major leap forward from the maximum 10-kilometre range that the lunar rover had on the moon. In this field, the company SpaceX is collaborating with the development of the NASA vehicle, instead of making its own proposal.

Nevertheless, the first step is to well establish the transportation method, and SpaceX will act in this sense as the transportation company, providing the best architecture for getting to Mars both cargo and crew. Starship is a spacecraft fully reusable, which will be able to carry more than 100 tones to Earth orbit – the analysis of the vehicle will be discussed in depth in section 5.2. Thus, SpaceX becomes the most capable company to carry out interplanetary transport, and therefore the most relevant short-range objectives are to manufacture and assemble the spacecraft, in such a way that it passes all the necessary tests to demonstrate the viability of the transportation method, as well as to ensure the integrity of the astronauts who will travel in it.

3.2 MISSION TIMELINE

When regarding to schedule a space project, it is important to take into account all possible events that could affect to the development of each phase of the mission, since this type of projects involve many variables. In the case of the Starship program, the timeline has been already planned and it is described below [8].

Figure 9 shows the main events contemplated in the Starship program, and then it is specified what they are based on and what must be achieved in each one of them.

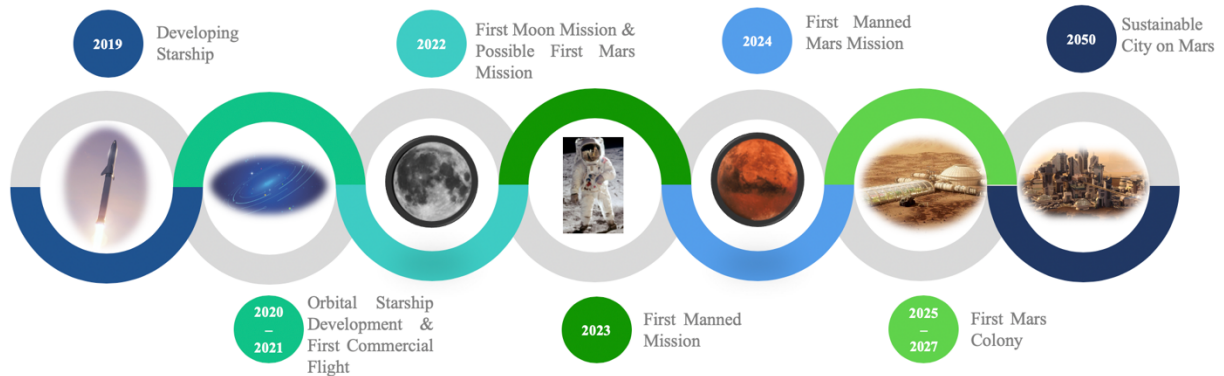


Figure 9. Timeline of Starship Program

2019: Developing Starship

SpaceX started building the Starship spacecraft prototype in 2019, at their South Texas facility in Boca Chica Beach, Texas, and at their development facility in Cocoa, Florida. They initiated by building Starhopper, a scaled down version of the spacecraft, so as to test the new Raptor engine. The first prototype had an eye-catching design with landing legs, but after a windstorm caused the top section of the spacecraft to blow over, the company decided to test just the bottom section, which was still useful after the storm. The Starhopper successfully passed the low altitude flight hop tests – the aim of this test is to jump as far as possible without losing balance and landing firmly – with a single Raptor engine. It was able to achieve 150 metres in the last hop test.

After the success on the tests performed to Starhopper, the company proceeded to build Starship Mk1 in Texas and Starship Mk2 in Florida, with three Raptor engines each of them. This spacecraft has a revolutionary new design, featuring fins. SpaceX planned to launch Starship 20 kilometres above Boca Chica before the end of 2019, but after it partially bursted during a pressurization test, the launching zone was reassigned to Florida, and both the Mk2 launching and the Mk3 construction were scheduled to next year.

2020 – 2021: Orbital Starship Development & First Commercial Flight

SpaceX is working on the next phase of Starship's development, which will include flight tests of Mk2 and Mk3 prototypes, as well as building the first prototype of the Super Heavy rocket booster – a description of this rocket will be presented in section 5.1. The rocket will be able to take Starship to high altitude with high velocity flights. It is planned for Starship to make its first orbital flight in 2020.

Starship could have its first commercial flight in 2021, in which it would launch a commercial satellite into space, according to the company announcement. In order to perform this launch, both Starship and the Super Heavy rocket booster need to be fully ready in optimal conditions. When the first commercial flight has been successful, will be proved the Starship's technology and design as a reliable alternative for carrying cargo to orbit.

2022: First Moon Mission & Possible First Mars Mission

This event is strongly dependent on the results of the previous one exposed, as if the first commercial flight results successful, NASA could choose SpaceX to launch cargo to the lunar surface, so as to help the government company in their Artemis program.

On the other hand, the company has mentioned that there is the intention of attempting a Moon landing before they start the Mars headed missions. As these interplanetary journeys are influenced by the relative position between the target and the departure planets, it is important to remark that next alignment between the Earth and Mars occurs in year 2022, and therefore SpaceX is shuffling the possibility of sending two unmanned Starship spacecraft to Mars surface, taking supplies to build life support infrastructure, power and fuel plants. They are also planning to send rovers to find water sources location in order to discover locations for future Starship arrivals.

2023: First Manned Mission

The company plans to send a group of astronauts in a circumlunar voyage aboard Starship, which will last about one week, and it is part of an art project named '*dearMoon*', conceived and financed by Yusaku Maezawa, a Japanese entrepreneur. In this journey, Starship will fly around 384,480 kilometres away from Earth, and it is planned to fly around the Earth before initiating the Earth-to-Moon transfer. Hence, it will be the most important Starship's flight to date.

2024: First Manned Mars Mission

In 2024 the Earth and Mars will be aligned again, and therefore it is a good opportunity for sending Starship spacecraft to the red planet. If in 2022 the company did not send the two Starship with cargo, it will be done this year; if they did send the spacecraft, it is planned to send two more cargo spacecraft and two manned Starship. Hence, whether or not the two spacecraft were sent in 2022, in 2024 it would be possible to take the first humans to Mars.

These astronauts will have the objective of setting up the base which will allow the survival in the red planet. On the other hand, they shall set up a propellant production plant so as to refuel Starship. This is an essential task for them, as they will need fuel to return home. They will have to set up gardens to grow food for survival, and they could use solar-powered hydroponics – a method which enables plants to grow without soil, and already used on the Earth – to construct greenhouses.

2025 – 2027: First Mars Colony

From SpaceX's perspective, by the year 2025 the Mars colony will be taking shape, and it could evolve into a small city with greenhouses and habitats that will enable more astronauts to arrive and live sustainably on the planet.

By the year 2027, and every two years from this, the company could send more spacecraft to the red planet, and, as the decade comes to an end, they expect to have a full settlement on Mars. It is important to note that SpaceX plans to have managed to build a total of 1,000 Starship spacecraft, so as to facilitate the construction of the Mars colony. Thus, they stand out they will take full advantage of all launch windows.

2050: Sustainable City on Mars

The company envisions that transforming humanity into a space faring civilization and building a sustainable city on Mars would be achieved by the year 2050.

SpaceX was founded under the belief that life is more exciting if humanity explores the stars, and colonizing Mars is beneficial to our species in order to expand borders and start looking for answers from a higher-level perspective.

3.3 ANALYSIS OF MISSION ARCHITECTURE

The analysis of the architecture planned for the mission is here below exposed, separating this study into different subsections which make up the core of the project. The first step is to analyse the mission through a preliminary study which will be useful to determine its feasibility [6]. Next, will be described each phase conducted during the interplanetary journey, in order to get as much information as possible to develop the next studies. Then, the method used so as to conduct the numerical study of the manoeuvring will be exposed.

3.3.1 Preliminary mission analysis and feasibility study

The main objective of this subsection is to schematically carry out a preliminary study of a spacecraft transfer from the Earth to Mars, determining a preliminary value for the total velocity change which has to be applied for conducting the mission. To do this, the study will be conducted applying a PCA (Patched Conic Approximation), described in the theoretical framework.

The departure and the arrival transfer for the mission are hyperbolic trajectories, in order to escape from the Earth and to enter to Mars – departure and arrival are not analysed in this preliminary estimation. As for the period when spacecraft orbits around the Sun, it is considered as a simple Hohmann transfer, an orbital manoeuvre that by means of two speed impulses is able to reach the destination orbit, starting from an initial parking orbit. It should be noted that so as to carry out this first analysis, two simplifying hypotheses are assumed: the first is that both the Earth and Martian orbits (around the Sun) are assumed to be circular, and the second is that both orbits are considered as coplanar; both hypotheses are assumable for a preliminary study, because the eccentricity and the difference in inclination between the two orbits are very low, and therefore it is acceptable to assume both as null values.

The process followed so as to perform the analysis is described in subsection 2.2.2, in which the equations used for studying a Hohmann transfer are described. In this hypothetical study, the architecture followed is defined as an elliptical trajectory which starts from an initial parking orbit around the Earth, at an altitude of 100 kilometres, and the destination orbit is a parking orbit around Mars, at an altitude of 300 kilometres. The inputs for conducting the study are the gravitational parameters of the three involved celestial body (i.e. the Earth's, Mars' and the Sun's gravitational parameters), the distance between the Earth and Mars (such that there is a true anomaly difference of π radians between the initial and final position of the transfer) and the altitude of the initial and of the destination orbit. The transfer orbit parameters that derive from the aforementioned conditions are the following:

Table 3. Orbital parameters of the transfer orbit

Parameter	Description	Value
r_1	Departure position	149606120 km
r_2	Arrival position	227993556.1 km
a_{HT}	Semi-major axis	188799838.05 km
e	Eccentricity	0.2076
p	Semi-latus rectum	180663456.43 km
v_1	True anomaly at point 1	0 rad
v_2	True anomaly at point 2	π rad

The main results obtained from the analysis are presented in Table 4.

Table 4. Results obtained for the preliminary mission analysis

Parameter	Description	Value
E_t	Energy of the transfer	$-351.47 \text{ km}^2/\text{s}^2$
v_A	Speed at initial parking orbit	29.78 km/s
v_B	Speed at final parking orbit	24.08 km/s
T_{trans}	Time of transfer	22371318.10 s
v_{HTA}	Heliocentric speed at departure	32.73 km/s
v_{HTB}	Heliocentric speed at arrival	21.47 km/s
Δv_A	Departure velocity impulse	2.95 km/s
Δv_B	Arrival velocity impulse	2.61 km/s
Δv_{tot}	Total velocity impulse	5.56 km/s

The trajectory plot obtained is presented in Figure 10. It is important to note that, since trajectories' plots have been performed maintaining the scale between the initial and final circular orbits and the elliptical transfer orbit, it is divided into three figures: the first ,in which only the transfer semi-ellipse is seen, the second in which it is observed the initial parking orbit and the start of the transfer and finally the third, in which the end of the transfer orbit and the destination parking orbit are presented.

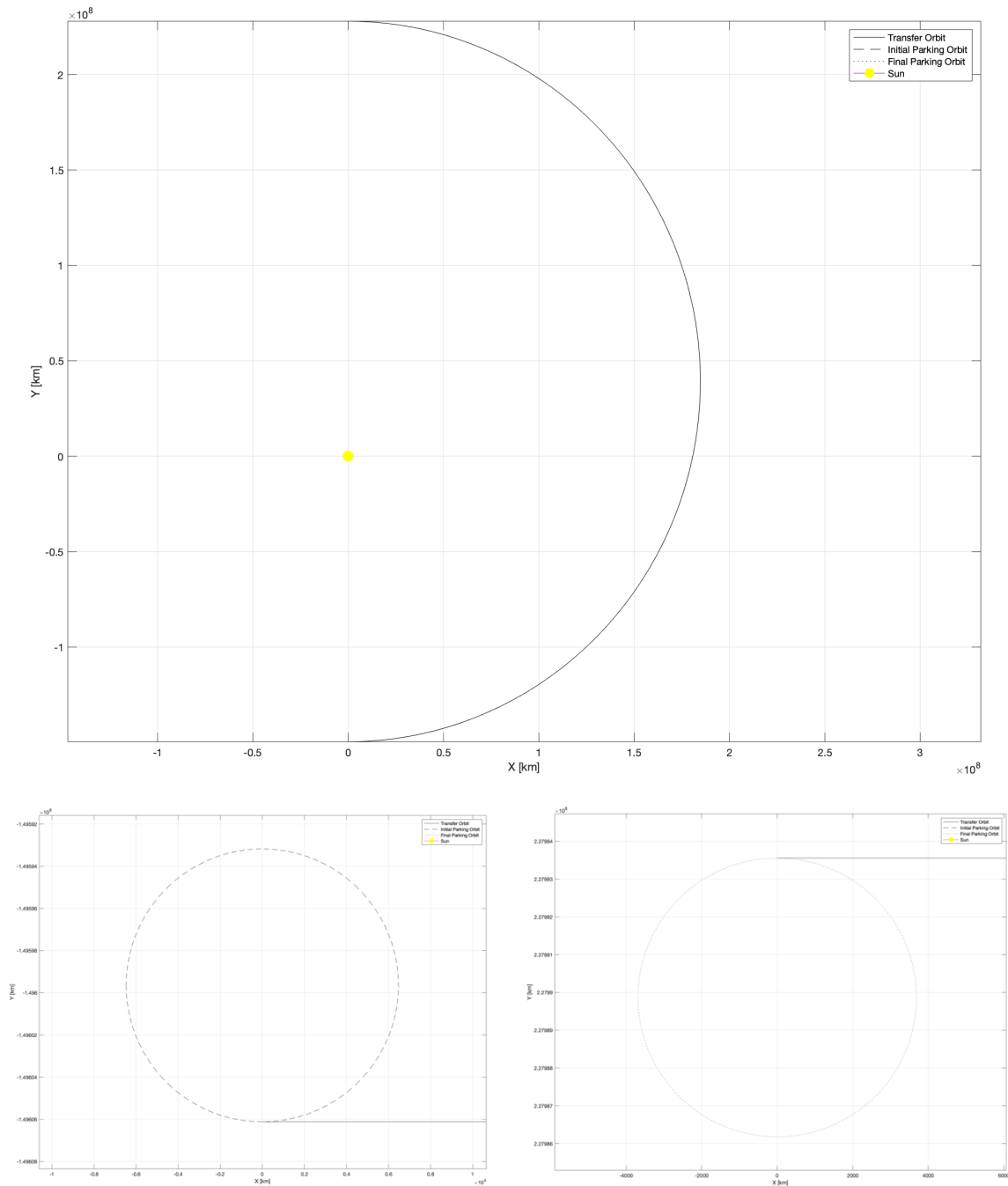


Figure 10. Preliminary mission analysis trajectory

From these results, which are the obtained from the most energy efficient possible Earth-to-Mars transfer, it is possible to perform an initial estimation of the total fuel required for this purpose. To do so, it is used the Tsiolkovsky equation (described in 2.2.7), which allows to obtain an approximate result for fuel consumption starting from the initial mass of the spacecraft and the exhaust velocity (depending on the specific impulse and nominal gravity acceleration). The needed inputs and the result obtained for the estimation of the required fuel are presented in Table 5.

Table 5. Fuel consumption preliminary estimation

Parameter	Value
Δv	$5.56 \text{ km/s} = 5560 \text{ m/s}$
I_{SP}	380 s
m_0	1320000 kg
m_f	297047.09 kg
$m_{burned \text{ fuel}}$	1022952.91 kg

It is important to remark that the specific impulse and the initial mass values are referred to Starship values, the spacecraft designed by SpaceX company (described in subsection 5.2), and they have been obtained from data shared by the company itself. As for the final mass value, it is an output of the Tsiolkovsky equation as well as the value for the total burned fuel (named as $m_{burned \text{ fuel}}$). This subsection ends concluding that, based on the results obtained, it is feasible to carry out the mission, taking into account that the Starship's capacity to store fuel is 1200000 kilograms, less than the required total fuel for the interplanetary transfer.

3.3.2 Deep study of each phase of the mission

In this subsection is presented the analysis of the different phases that make up the mission architecture planned by SpaceX to be carried out with the Starship and the Super Heavy rocket. The main objective is to describe each of these phases in as much detail as possible, thus obtaining a global perspective that will facilitate the approach of the numerical study which is carried out in the following subsection [11].

It is presented as a summary of the global architecture the interrelated visual diagram of the whole mission, in Figure 11, in order to obtain a global perspective of the mission architecture proposed by SpaceX for reaching Mars.

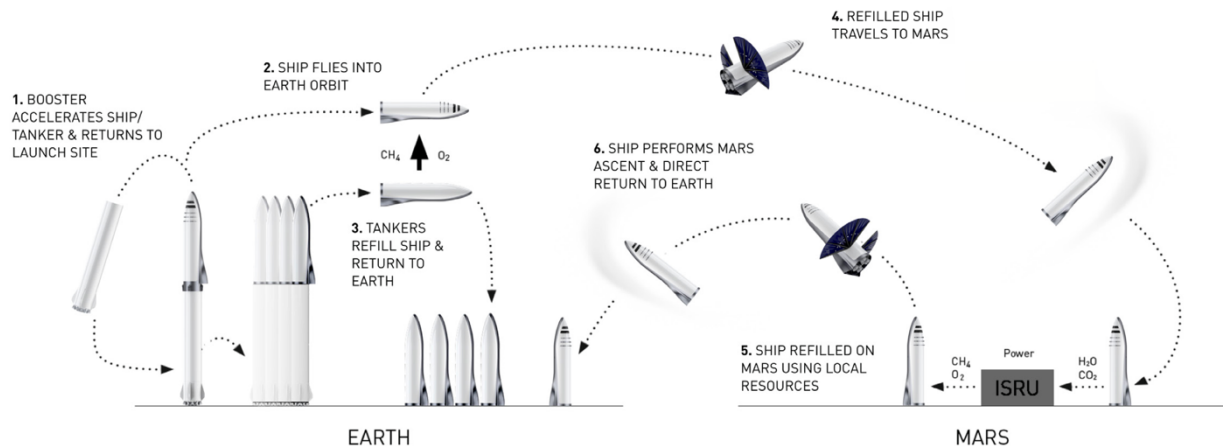


Figure 11. Diagram of the mission architecture [11]

Overall, the mission architecture could be described as a semi-direct ascent, since the ultimate goal is to land directly on the Martian surface without previously orbiting Mars. However, it cannot be considered as complete direct ascent, because Starship requires to be refuelled while orbiting Earth. Each phase is described separately below.

1. Starship launch



Figure 12.
Launch phase

The ship is fully loaded, both the crew and the payload that will be taken to Mars are ready to start the mission. The booster accelerates the spaceship and, once the fuel of first stage has been consumed, the separation between Super Heavy rocket and Starship occurs. While the spaceship starts its engines and moves to the initial destination parking orbit (LEO orbit), the booster begins the reentry manoeuvre to the Earth's surface. It is important to note that, Thanks to the reentry system developed by SpaceX, the first stage of the launch will be fully reusable, thus allowing not only to lower the costs of the mission but also to speed up its duration. In Figure 12, the schematized launch phase can be seen.

2. Starship refuelling

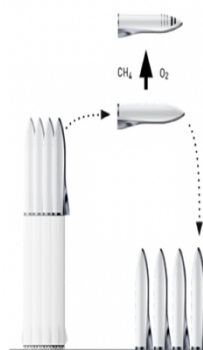


Figure 13.
Refuelling phase

As mentioned before, the Starship is now orbiting in an initial parking orbit. So as to complete this phase, when the first stage booster lands, it is prepared for launching again, taking to orbit an alternative Starship model, which is specially designed for carrying fuel. Once the booster is ready, the process followed is similar to that described for the first spaceship, but in this case, once the first stage is separated, the spaceship aims to perform a rendezvous and subsequent docking manoeuvre with Starship, in order to refill its fuel tanks, returning later to Earth's surface. It is important to note that this procedure is repeated as many times as necessary until the main Starship tanks are completely full. The company has estimated that with a total of four fuel refilling manoeuvres this phase would be completed; nevertheless, this data should be considered as a guideline, pending further testing. Figure 13 presents the scheme of this phase.

3. Starship transfer to Mars

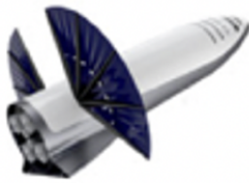


Figure 14. Starship Mars transfer

Once Starship's fuel tanks have been fully recharged, the spaceship is ready to begin its journey to the red planet. This is the longest phase of the mission, depending on the date chosen to complete it, as it is important to consider the relative position between the Earth and Mars. In Figure 14, it can be seen the proposed spaceship configuration for the transfer to Mars phase, where solar panels are deployed so as to supply energy to the different Starship subsystems. Electrical power generation and storage are described in subsection 5.5.

4. Starship Mars entry and landing



Figure 15. Mars entry and landing

In the phase of Mars entry, the speed of the spaceship will be high, since instead of orbiting the planet to then proceed to landing, the spaceship will land on the surface of Mars directly [24]. Therefore, it is important to consider that it will be subject to high temperatures, once it has come into contact with the Martian atmosphere. The spaceship's heat shield is out of the scope of this thesis, but it is a topic in which the company is investing many resources. As for the landing phase, it is important to note that landing on Mars is not an easy task – until now, only NASA has been able to successfully land functional payload on the surface of the red planet. SpaceX plans to perform an attitude change manoeuvre, orienting Starship in such a way that its engines are focused towards the planet surface, and to perform a supersonic retro-propulsion manoeuvre. In Figure 15 a visual representation of this phase is presented.

5. Preparing return to Earth

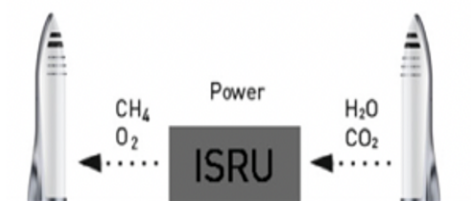


Figure 16. Preparing return to Earth from the Martian surface

Once Starship has landed in the Martian surface, it is time for developing all the planned operations of the mission. Meanwhile, the spaceship is prepared to do the return to Earth. To this end, it is necessary to have already built certain systems on Mars, which have already been mentioned, but the most important in terms of mission architecture is the fuel production plant. By using this infrastructure, it is possible to refill the spaceship utilizing in-situ resources to carry out the return trip. The in-situ fuel obtainment is described in subsection 5.6. In Figure 16 the schematic representation of the phase can be seen.

6. Departure from Mars

When the objectives of the mission have been completed and the Starship is full of fuel, it is time to start the return trip. Again, it is important to consider how and when to perform the ascent manoeuvre from the Martian surface, since depending on the relative position between Mars and Earth it will take more or less to arrive.

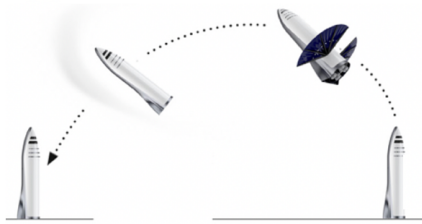


Figure 17. Departure from Mars and arrival to Earth

7. Arrival to Earth

To land on the Earth's surface, a direct return manoeuvre is used, since in this case the spaceship goes directly from the Martian surface to the Earth, without any intermediate phase. The Earth's atmosphere is denser than Martian, and therefore the thermal shield implemented in Starship must be able to withstand the high temperatures to which it will be subjected in the phase of re-entry to Earth. In Figure 17, both the departure from Mars and the arrival to the Earth is presented schematically.

3.3.3 Architecture Analysis Tool

In this subsection, it is described the global tool developed in Matlab so as to analyse the manoeuvres which are conducted through the different phases of the SpaceX mission to reach Mars. The codes used for each study are presented in the annexes document, and the main results obtained from them are shown in section 4, in which the architecture proposed by the company for the Starship project is analysed following the aforementioned timeline.

The script of this subsection follows the logical structure developed when solving the interplanetary transfer using a PCA approach; that is to say, trying to decouple as much as possible the different situations in which spacecraft finds itself on its path to destination (in this particular case, Mars), for later apply certain hypotheses that allow them to finally fit. The strategy conducted for the analysis is first solving the Lambert problem, then obtaining the hyperbolic escape trajectory and the hyperbolic approach trajectory, and finally study the launching, the rendezvous manoeuvre for filling the fuel tanks analysis and the Mars entry process study.

Lambert solver

For solving the Lambert problem, it is used a Newton-Raphson iterative process, while implementing a differential corrector together with a continuation method. All techniques are described in the theoretical framework. In Figure 18 it is shown the generic diagram of the implemented solver, which synthesizes the sequence of steps of the procedure performed.

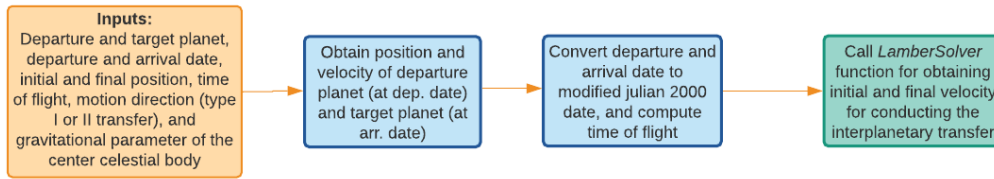


Figure 18. Global Lambert solver flow chart

Once the *LambertSolver* function has been called, the iterative process for obtaining the initial and final velocity for conducting the interplanetary transfer starts. It is schematized in Figure 19 [10].

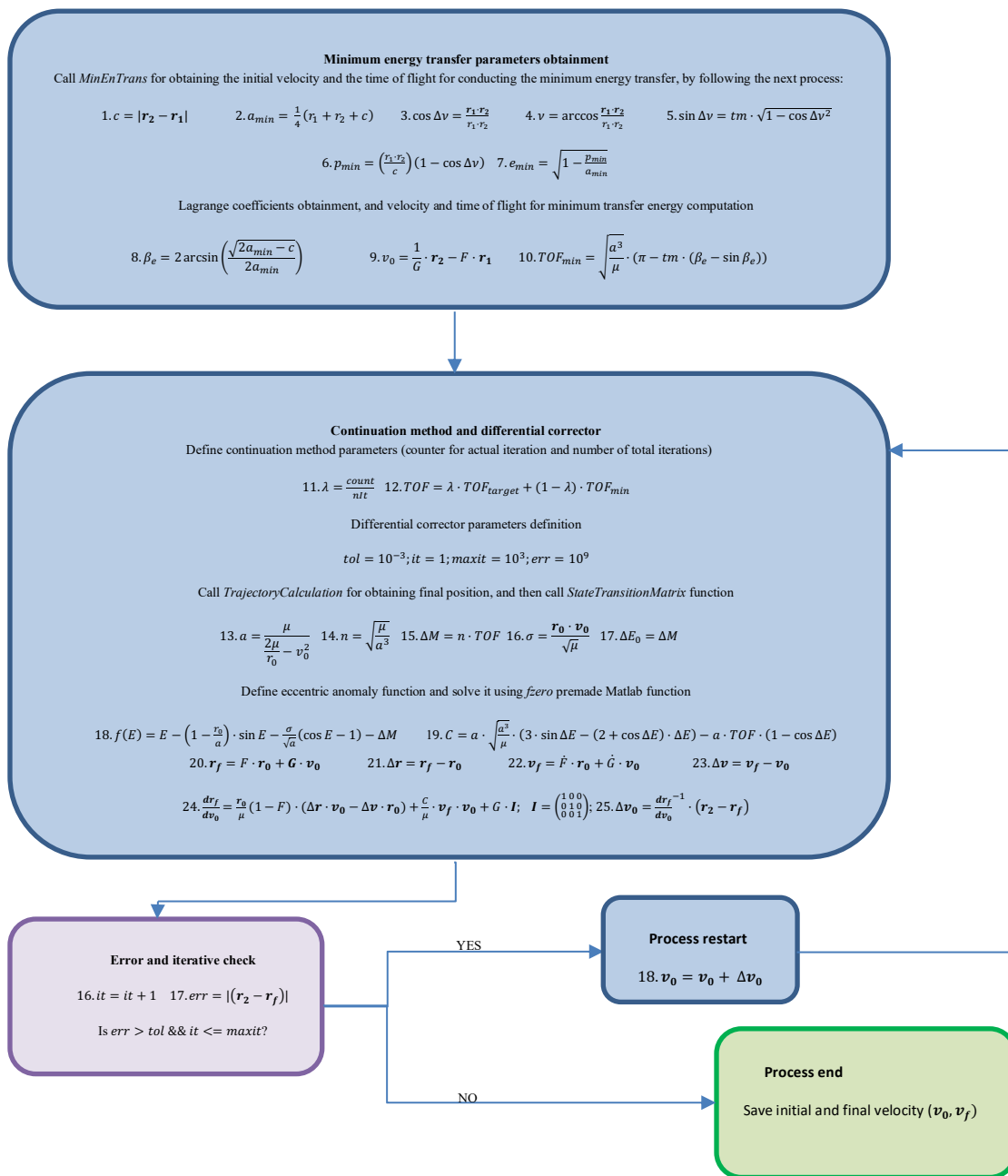


Figure 19. Detailed Lambert solver flow chart

Launch windows obtainment

Once the Lambert problem is solved, it is necessary to decide what are the best possible options to carry out the mission. For this, it is necessary to introduce the concept of pork-chop plot.

A pork-chop plot represents the first menu item for planning a trip to Mars. It is a graphical representation of the possible launch windows for performing an interplanetary transfer. To develop this plot, it is necessary to be able to solve the Lambert problem for a large number of iterations. By defining a specific time period and a maximum duration to perform the interplanetary transfer, a grid of launch opportunities and a grid of arrival dates are created, and by solving the Lambert problem a total impulse velocity is obtained for each case. Therefore, creating a coloured plot, the best launch opportunities are easily observable. It is also possible to define a maximum velocity impulse so as to filter the obtained results. In Figure 20 it is shown a diagram which shows the structure of the code developed for obtaining pork-chop plots.

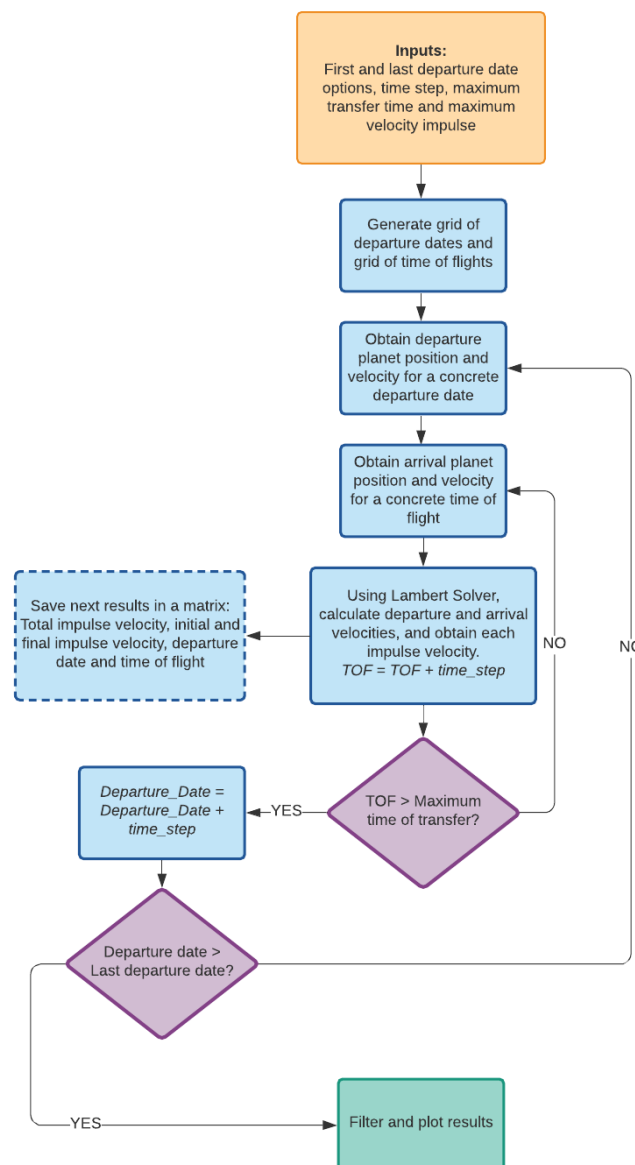


Figure 20. Launch windows obtainment flow chart

Hyperbolic escape and approach trajectories

As for the hyperbolic escape and approach trajectories, it is important to note that several hypotheses have been considered, in order to correct-apply the patched conic approximation. The hypotheses applied are firstly that the velocities v_1 and v_2 obtained from the Lambert solver are equal to the hyperbolic velocity $v_{\infty 1}$ and $v_{\infty 2}$ of both hyperbolic trajectories, and secondly, at the limit of the spheres of influence of each planet, velocity at the left limit equals velocity at the right limit (i.e. the velocity just before entering the planet's sphere of influence is equal to the right velocity after entering that sphere of influence). Therefore, once applied these conditions, it is possible to obtain the trajectory followed by the spacecraft in both the escape hyperbola from the Earth and the approach to Mars hyperbola. In Figure 21 is presented the diagram which shows the algorithm developed for obtaining the trajectory results [25].

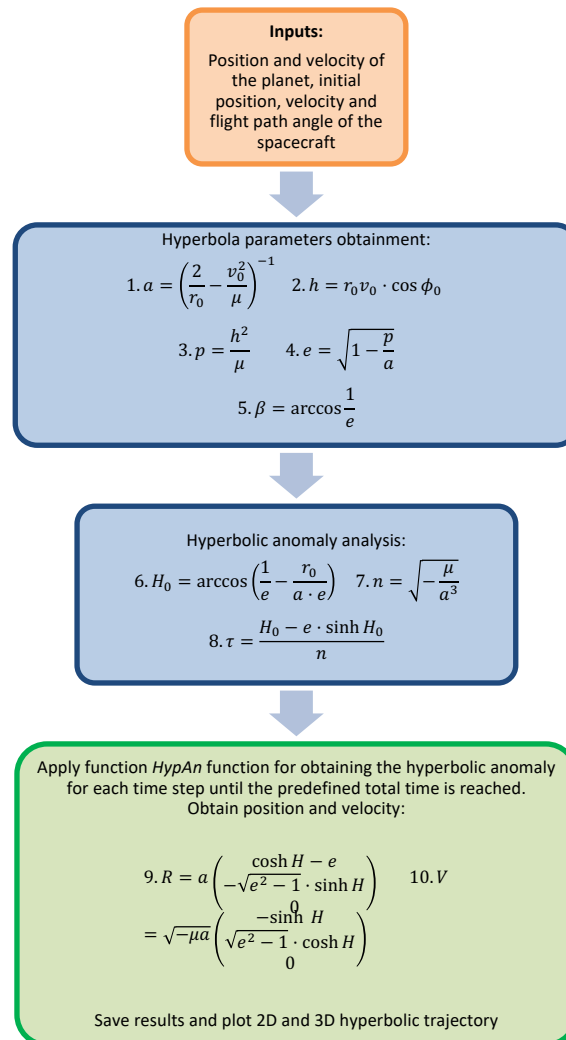


Figure 21. Hyperbolic trajectory flow chart

Starship launching

When regarding to analyse the launching, it is important to remark that there is not much information available to carry out this phase-study of the architecture. An estimated analysis has been carried out based on the inputs shared by the company, which are the specific impulse of the Super Heavy rocket and the spacecraft Starship, the total mass of both structures and their capacity for storing fuel. The process conducted so as to obtain the needed inputs is described below. Starting from the available data, the mass variation of each stage is obtained, considering the previously exposed assumptions, using the next equation:

$$I_{SP} = \frac{T}{\dot{m}g_0} \Rightarrow \dot{m} = \frac{T}{I_{SP}g_0} \quad (3.1)$$

Then, it is possible to obtain the burnout time, which is a parameter that can be varied so as to modify the launching characteristics. Assuming the mass flow rate as a design constant, it can be obtained from:

$$\dot{m} = \frac{m_f - m_i}{\Delta t} \Rightarrow \Delta t = \frac{m_f - m_i}{\dot{m}} \quad (3.2)$$

In Table 6 are presented the main inputs needed for solving and the Earth ascent study. It is important to note that the values for the Δt_{bo} are the calculated taking into account the assumptions that the first stage reserves 7% of fuel to perform the landing (thus ensuring its reusability), and that the spacecraft reserves a 10% of fuel for, once located in the destination parking orbit, maintaining the correct path for waiting to be refilled with fuel.

Table 6. Inputs required for launching study

Parameter	Super Heavy Rocket (first stage)	Starship (second stage)
Total mass (m) [kg]	4850000	1320000
Propellant mass (m_p) [kg]	3300000	1200000
Mass flow rate (\dot{m}) [kg/s]	22248.35	3220.16
Specific impulse (I_{SP}) [s]	330	380
Time burnout (Δt_{bo}) [s]	137.94	335.39
Thrust (T) [N]	72000000	12000000

Once these values have been obtained, the equations of motion are defined and solved by using the ode45 function, which is a premade Matlab function. Also, it is needed to implement an atmospheric model, in order to perform the study, that will be described in the entry study description. By setting up a desired parking orbit height, it is possible to obtain the height, velocity, and flight-path angle versus time plots.

Rendezvous manoeuvring

As mentioned before, once the Starship is in the initial parking orbit, it is necessary to be refuelled. Therefore, it is needed a rendezvous and docking manoeuvre. The docking is not studied in this thesis, as it is out of the general scope. In order to perform the rendezvous analysis, it is considered as a Hohmann transfer from an initial parking orbit (in which the uncrewed configuration Starship is first launched) to the parking orbit of the crewed Starship (in which it is waiting for the fuel refill). In Figure 22, it is presented the diagram which resumes the main steps of the developed code for solving this phase.

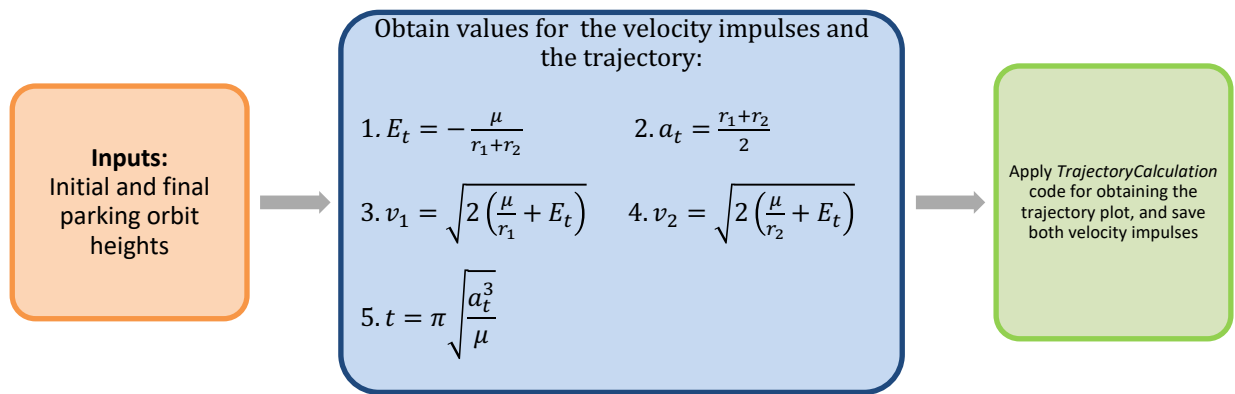


Figure 22. Rendezvous study flow chart

Entry process

Regarding the entry study [23], it is important to mention that it has been carried out for both, the phase of arrival on Mars and the phase of return to Earth. The main reason is that for the validation process of the developed code, it was easier to access data of entry processes into the Earth's atmosphere. Once this validation was carried out, the different codes developed were adapted to study the process on Mars. It should be noted that a large amount of data was available to develop the Earth's atmospheric model, while fewer data was available to develop the Martian atmospheric model, and therefore the results obtained for the study on Mars are not entirely satisfactory. This section presents the process followed for both studies.

The first step is to develop the Earth atmospheric model [25]. In Table 7, the inputs needed for performing this model are presented.

For each height, the density is computed following the next mathematical procedure:

First, the gravity must be computed:

$$g = g_0 \left(\frac{r_0}{r_0 + h} \right)^2 \approx g_0 \left(1 - \frac{2h}{r_0} \right) \quad (3.3)$$

Table 7. Earth standard atmosphere parameters

H [km]	T [K]	R [J/(kg·K)]	α_T [K/km]
0	288.15	287	-6.5
11	216.65	287	0.0
20	216.65	287	1.0
32	228.65	287	2.8
47	270.65	287	0.0
51	270.65	287	-2.8
71	214.65	287.02	-2.0
86	186.946	287.02	1.693
100	210.02	287.84	5.0
110	257.0	291.06	10.0

H [km]	T [K]	R [J/(kg·K)]	α_T [K/km]
120	349.49	308.79	20.0
150	892.79	311.80	15.0
170	1103.4	321.57	7.0
190	1205.4	336.68	5.0
230	1322.3	366.84	4.0
300	1432.1	416.88	3.3
400	1487.4	463.36	2.6
500	1506.1	493.63	1.7
600	1506.1	514.08	1.1
700	1507.6	514.08	0.0

Then, integrating the equation of the hydrostatic equilibrium (between an initial height and pressure, and the final pressure and height), it is possible to compute the pressure:

$$p = p_i \left[1 + \frac{a(h - h_i)}{R T_i} \right]^{-\left(\frac{g_0}{a \cdot R} \left[1 + \beta \left(\frac{T_i}{a} - h_i \right) \right] \right)} \cdot e^{\frac{\beta g_0}{a \cdot R} (h - h_i)} \quad (3.4)$$

It can be particularized if the thermal lapse rate (a) is equal to zero:

$$p = p_i e^{-\left[\frac{g_0(h - h_i)}{R \cdot T_i} \right] \left[1 - \frac{\beta(h - h_i)}{2} \right]} \quad (3.5)$$

Finally, the density is obtained from the ideal gases law:

$$\rho = \frac{P}{RT} \quad (3.6)$$

Nevertheless, as commented before, for the Mars' atmosphere it has not been possible to obtain the inputs required for adapting the same model described above. For that reason, it is needed to develop a new atmosphere model, described below [21]. The main objective is to obtain the density for each height range. It should be noted that in the reference used for obtaining the Mars atmospheric model is separated two layers: the lower one, up to a height of 120 km, and the upper one, from 120 km to 300 km, based on the data obtained by the *Viking-1*. In Table 8 the equations used for obtaining the temperature and the pressure for each height range of the lower layer are presented.

Table 8. Mars atmosphere model lower layer parameters calculation

H [km]	T [K]	P [Pa]
0-39	$228.50 - 1.80 * h$	$610.5 \left(\frac{228.5}{228.5 - 1.8 * h} \right)^{\frac{19.435}{-1.8}}$
39-48	158.30	$11.6025 \cdot e^{\frac{-19.435 * (h-39)}{158.3}}$
48-55	$271.10 - 2.35 * h$	$3.84305 \left(\frac{158.3}{158.3 - 2.35 * (h - 48)} \right)^{\frac{19.435}{-2.35}}$
55-66	$106.10 + 0.65 * h$	$1.55091 \left(\frac{141.85}{141.85 + 0.65 * (h - 55)} \right)^{\frac{19.435}{0.65}}$
66-75	$314.00 - 2.50 * h$	$0.356464 \left(\frac{149}{149 - 2.5 * (h - 66)} \right)^{\frac{19.435}{-2.5}}$
75-84	$-61.00 + 2.50 * h$	$0.0998430 \left(\frac{126.5}{126.5 + 2.5 * (h - 75)} \right)^{\frac{19.435}{2.5}}$
84-95	149.00	$0.0279653 \cdot e^{\frac{-19.435 * (h-84)}{149}}$
95-105	$282.00 - 1.40 * h$	$0.00667032 \left(\frac{149}{149 - 1.4 * (h - 95)} \right)^{\frac{19.435}{-1.4}}$
105-120	$203.25 - 0.65 * h$	$0.00169282 \left(\frac{135}{135 - 0.65 * (h - 105)} \right)^{\frac{19.435}{-0.65}}$

With the results of temperature and pressure for the lower layer, it is obtained the specific heat ratio and the density for each height following the next mathematical process:

$$\gamma_T = 0.000001409 * T^2 - 0.001192 * T + 1.5175 \quad (3.7)$$

$$R = 191.181 \frac{J}{Kg \cdot K} ; \rho = \frac{P}{RT} \quad (3.8)$$

As for the upper layer, in Table 9 the equations used for calculating the temperature, the pressure and the density are presented.

Table 9. Mars atmospheric model upper layer parameters calculation

H [km]	T [K]
120-200	$200 - 72.225 * e^{-0.0195 * \xi}$; where $\xi = (h - 120) * \frac{3389.51 + 120}{3389.51 + h}$
200-300	

H [km]	P [Pa]
120-200	$e^{-4.18 \cdot 10^{-10} \cdot h^5 + 3.45 \cdot 10^{-7} \cdot h^4 - 1.13 \cdot 10^{-4} \cdot h^3 + 0.02 \cdot h^2 - 1.72 \cdot h + 61.12}$
200-300	$e^{-4.83 \cdot 10^{-11} \cdot h^5 + 6.96 \cdot 10^{-8} \cdot h^4 - 4.03 \cdot 10^{-5} \cdot h^3 + 0.01 \cdot h^2 - 1.76 \cdot h + 93.67}$

H [km]	ρ [kg/m ³]
120-200	$e^{-2.55 \cdot 10^{-10} \cdot h^5 + 2.32 \cdot 10^{-7} \cdot h^4 - 8.33 \cdot 10^{-5} \cdot h^3 + 0.02 \cdot h^2 - 1.53 \cdot h + 48.7}$
200-300	$e^{2.65 \cdot 10^{-11} \cdot h^5 - 2.45 \cdot 10^{-8} \cdot h^4 + 6.31 \cdot 10^{-6} \cdot h^3 + 4.73 \cdot 10^{-4} \cdot h^2 - 0.44 \cdot h + 23.79}$

Once the density for each height has been obtained, it is possible to calculate the sound velocity, the Mach number and the Knudsen number, which determines the flow regime parameter. With these parameters, that are used for determining the aerodynamic forces for each height range, the atmospheric model is closed. In order to obtain the time-derivatives of the height, of the velocity and the flight path angle, the equations of motion are defined (presented in subsection 2.2.6) and by using the premade Matlab function *ode45* they are integrated for a concrete time span.

It is important to note that the way of performing the entry is considered, since modifying the equations of motion it is possible to simulate a ballistic entry or a manoeuvring entry. The main difference is that in the first case the spacecraft is considered as a rocket that does not produce hardly lift, and therefore this aerodynamic force is neglected from the equations. In contrast, for a manoeuvring entry, the lift is a remarkable force, and therefore is added to the equations of motion. However, the solving process is equal for both cases, and the only variation between them is found in the equations of motion. In Figure 23 it is presented the flow chart which resumes the computational steps of the entry phase study.

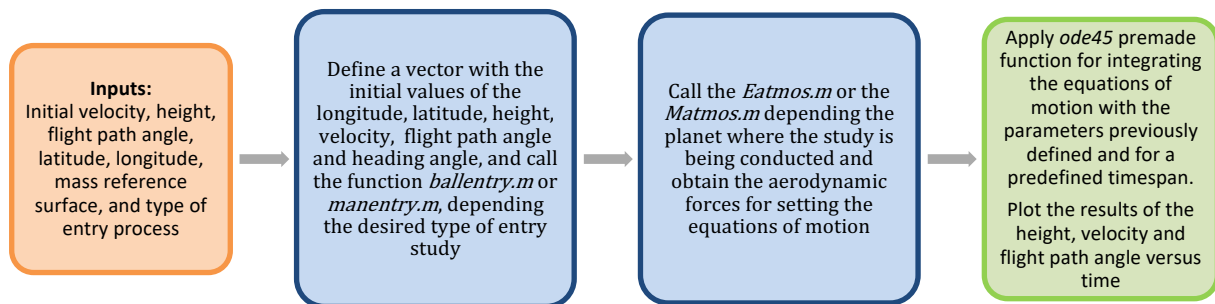


Figure 23. Entry study flow chart

4 ARCHITECTURE PROPOSAL STUDY

In this section, it is presented the architecture proposal developed, following the SpaceX timeline. Firstly, a proposal is made to meet the objectives set by the company, developed assuming certain hypotheses that will be discussed throughout the section. Next, the main global results for the interplanetary transfer are presented, and finally the complete analysis of an Earth to Mars interplanetary transfer is carried out, with the aim of showing the main outputs and the graphic results that can be obtained using the tool developed throughout the thesis. These results include the launch opportunities for the Starship spacecraft, the transfer from the Earth to Mars for each predefined launch, the hyperbolic trajectories, the launching of the spacecraft together with the rocket, and the entry process. It is important to note that the process followed for obtaining all results presented in this section are explained in detail in subsection 3.3.3, and the codes developed are presented in the annexes document.

4.1 MARS' COLONIZATION PROCESS

This subsection is addressed to establish a proposal for colonizing Mars. To do so, the schedule follows the timeline proposed by SpaceX – available in subsection 3.2. The main milestones to achieve are summarized in Table 10.

Table 10. Main milestones to complete during Mars' colonization

Milestone	Description	Development period	Code
Settlement on Mars	Two uncrewed Starships are sent to Mars so as to prepare the astronauts arrival	2022-2024	M1
Mars' initial colony	Two crewed Starships are sent to Mars for testing the settlement and eight more Starships are later sent	2025-2027	M2
Mars' sustainable city	All needed Starships are gradually sent to Mars until achieving the proposed goal of total habitants on Mars	2027-2050	M3

Several considerations are made so as to accomplish the different milestones described:

- Each Starship is able to transport 100 people per interplanetary transfer.
- The objective to be achieved in the creation of the first colony by year 2027 is to reach 1,000 habitants.
- The final goal to consider that the objective of creating the first sustainable city on Mars is accomplished when Mars' population reaches 100,000 habitants by year 2050.
- The technologies required to develop and keep colonization of the red planet feasible are not described. Rather, they are assumed to be fully available to carry out the mission.
- The rate of population growth is considered to be linearly increasing, following the trend line presented below.

- Only the process of arrival of people to Mars is considered, assuming that people who arrive on the planet stay and do not come back to Earth until the sustainable city have been fully established.
- The manufacturing rate of Starships and Super Heavy rockets is assumed to be 50 complete vehicles per year.

Regarding the rate of Mars' population growth, as commented before, is considered to follow a linear trend. However, the first two milestones are not governed by said linear trend. During the M2 milestone, in the first crewed mission to Mars, 2 Starships arrive to the red planet. It is considered that both carry as many passengers as possible – i.e. a total of 200 astronauts arrive to Mars. As for the second period, when the first colony is being created, eight Starships, again carrying 100 astronauts each, arrive to Mars. Therefore, the period which follows the linear trend is the last one, the Mars' sustainable city creation. In order to estimate the required number of people sent per year necessary to meet the proposed objective, it is developed a linear approximation. It is important to consider that, when the M3 milestone starts, there are already 1,000 people on Mars. In Figure 24 the linear approximation is presented.

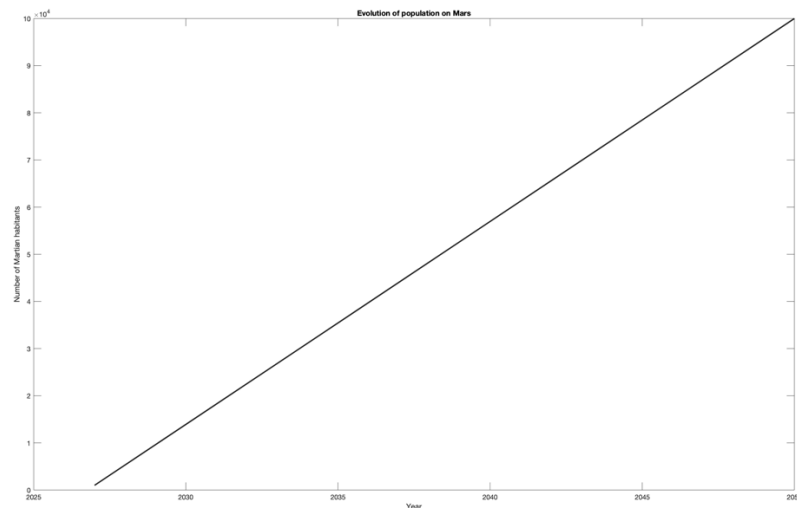


Figure 24. Mars' population evolution

The Mars' population evolution is summarized in Table 11, in which can be seen the total number of habitants on Mars at the beginning and at the end of each milestone.

Table 11. Mars' population per milestone

Milestone	Initial Mars' population	Final Mars' population
M1	0	0
M2	0	1,000
M3	1,000	100,000

4.2 GLOBAL RESULTS

Once the initial timeline and the population growth rate have been defined, is conducted the global analysis for each interplanetary transfer. First of all, for each milestone described above, a study of the launch windows should be carried out, in such a way that all possible departure and arrival dates are presented to carry out each interplanetary transfer. It should be noted that the criterion followed to decide on the launch date is to minimize fuel consumption, maximizing thus the energetic efficiency, giving less importance to the total flight time. A maximum time of flight of 300 days has been defined, since Starship ships are able to withstand space conditions for longer. However, optimizing resources is preferred as there is no apparent reason to rush arrival on each journey. In Figure 25, Figure 26 and Figure 27 the porkchop plot of initial impulse velocity per each milestone is presented. It should be noted that the porkchop plots presented show the initial impulse velocity, but the data has been filtered in such a way that only those launch windows which require a total velocity impulse less than or equal to 10 km/s are shown.

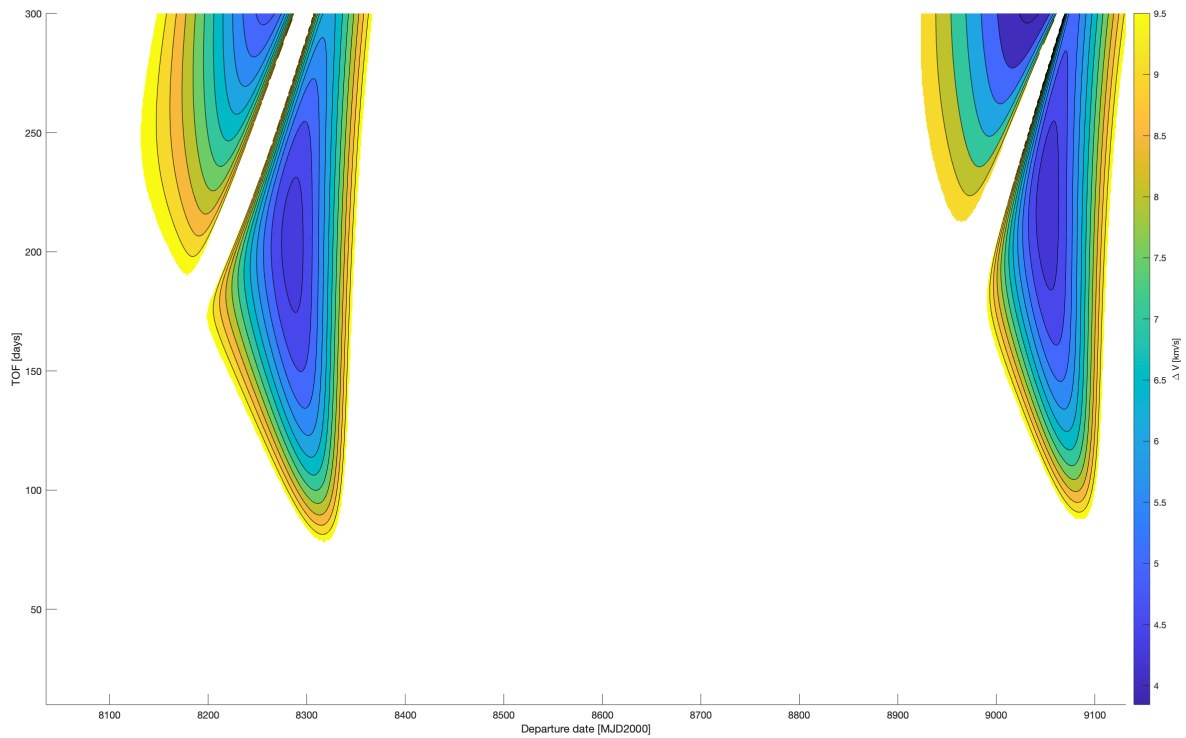


Figure 25. Initial velocity impulse porkchop plot 2022-2024 [M1]

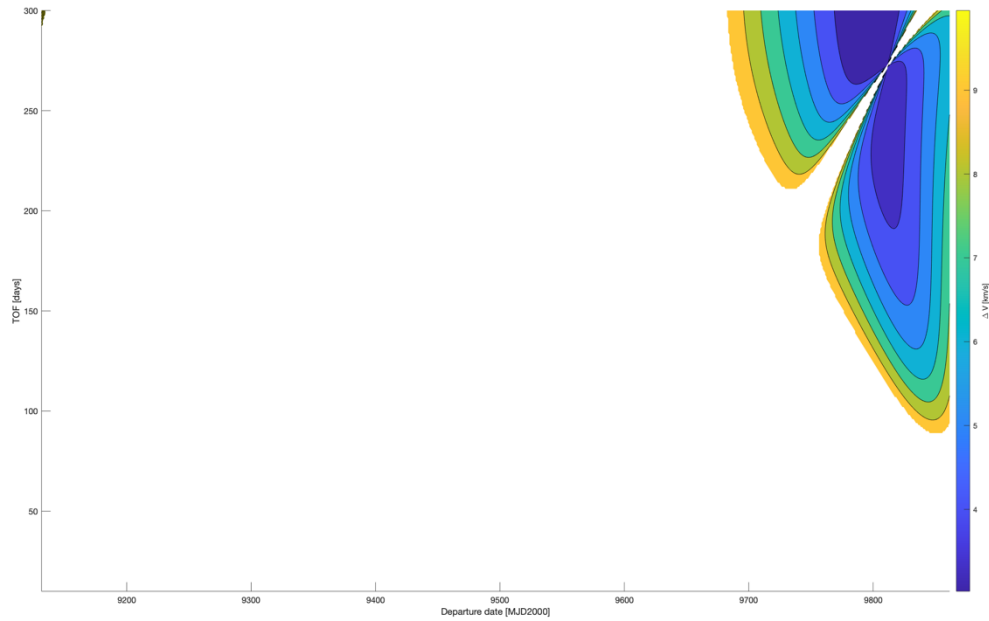


Figure 26. Initial velocity impulse porkchop plot 2025-2027 [M2]

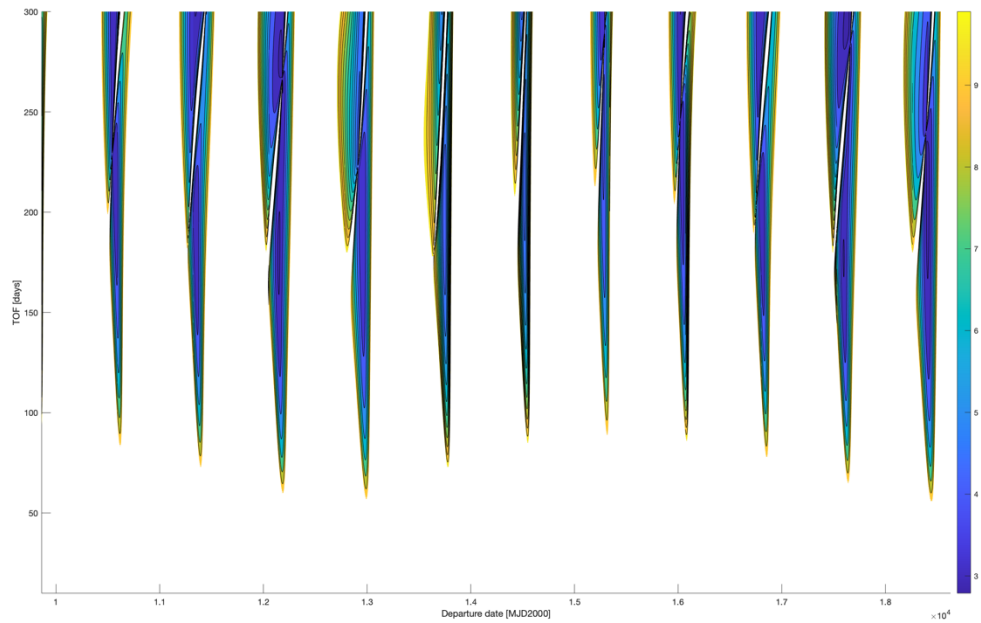


Figure 27. Initial velocity impulse porkchop plot 2027-2050 [M3]

Following the aforementioned criterion, the departure and arrival date of all interplanetary transfers are selected, thus setting a certain velocity impulse for each of them. In Table 12, the global results per each required transfer so as to accomplish the milestones are presented.

Table 12. Global results for interplanetary transfers

Period	Number of Starships sent	People sent to Mars	Departure date	Arrival date	Total Δv [km/s]	Initial Δv [km/s]	Final Δv [km/s]	Fuel per one transfer [kg]	Total fuel [kg]
2022-2024	2	0	18/9/2022	7/5/2023	7.283	4.578	2.705	1132891.66	2265783.33
2024-2025	2	200	21/9/2024	16/7/2025	6.849	3.933	2.916	1109789.3	2219578.61
2025-2027	8	800	2/11/2026	19/8/2027	5.756	3.043	2.713	1038617.55	8305340.36
2027-2029	87	8700	9/11/2028	28/8/2029	6.351	3.308	3.043	1079744.92	93937808
2029-2031	87	8700	19/12/2030	30/9/2031	6.772	3.410	3.362	1105402.12	96169984.4
2031-2033	87	8700	18/1/2031	29/10/2031	7.196	3.217	3.979	1128473.55	98177198.4
2033-2035	87	8700	17/4/2033	8/11/2033	6.361	3.042	3.319	1080388.55	93993804
2035-2037	87	8700	26/6/2035	14/1/2036	5.850	3.225	2.625	1045185.36	90931126.7
2037-2039	87	8700	3/9/2037	11/4/2038	7.008	4.372	2.683	1118566.8	97315311.2
2039-2041	87	8700	3/9/2039	26/6/2040	7.381	4.480	2.901	1137746.46	98983941.6
2041-2043	87	8700	22/10/2041	14/8/2042	5.893	3.216	2.677	1048337.13	91205330
2043-2045	87	8700	21/11/2043	10/9/2044	5.852	3.068	2.784	1045332.77	90943950.6
2045-2047	87	8700	20/12/2045	7/10/2046	6.42	3.104	3.316	1084151.04	94321140.1
2047-2050	87	8700	19/3/2048	3/10/2048	6.952	3.185	3.767	1115517.97	97050063.7

As can be seen, the results for total impulse velocity are similar for each interplanetary transfer, since the criterion for choosing the departure and arrival date is maintained in each study. In order to avoid excessive repetition of similar data, it has been decided to present the specific results of the complete analysis of a single interplanetary transfer, choosing it at random, in order to demonstrate the potential of the tool developed to analyse interplanetary missions. Both numerical and graphical results for the Earth-to-Mars trip for the 2037-2039 period are presented in the following subsection. By using the developed tool, the results of the analysis for all phases of each transfer could be obtained, obtaining similar results.

4.3 COMPLETE STUDY FOR PERIOD 2037-2039

In order to properly conduct the complete analysis of this period, it is performed again the launch windows study, presenting the porkchop plot for the total Δv , the initial Δv and the final Δv , presented in Figure 28, Figure 29 and Figure 30, respectively.

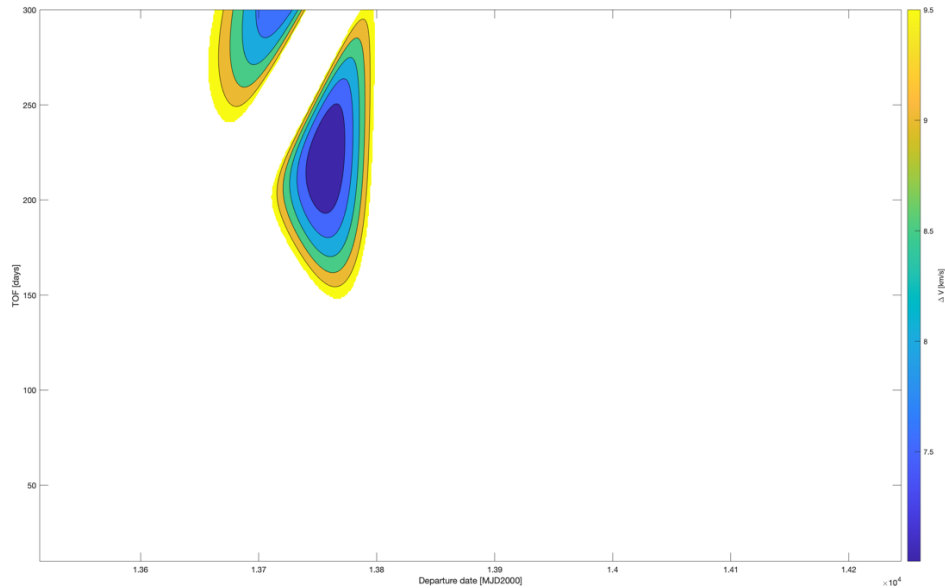


Figure 28. Porkchop plot 2037-2039 total impulse velocity

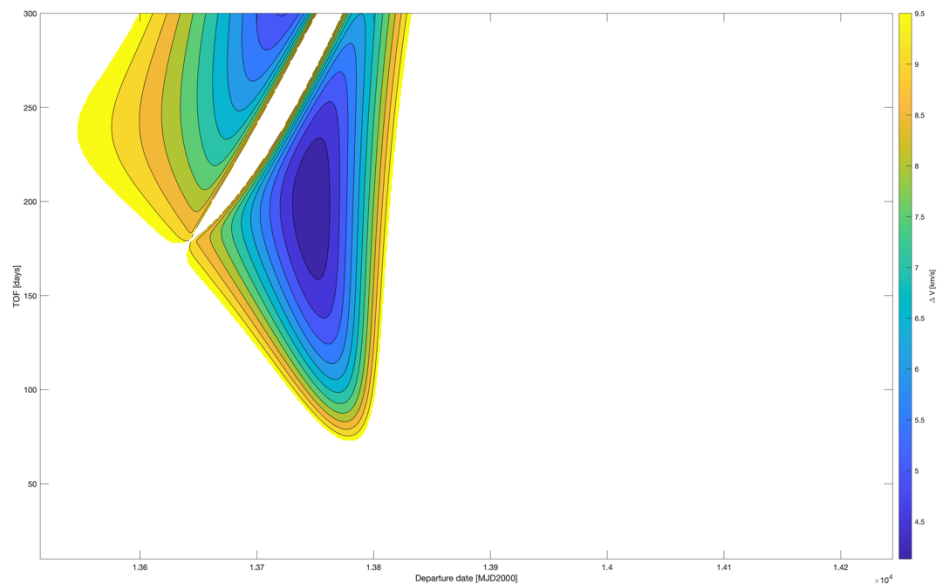


Figure 29. Porkchop plot 2037-2039 initial impulse velocity

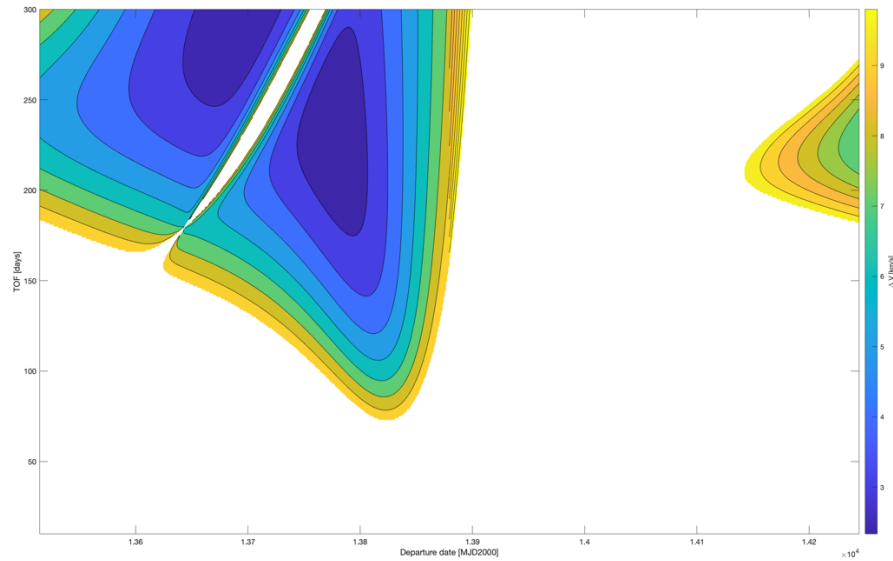


Figure 30. Porkchop plot 2037-2039 final impulse velocity

From these results, maintaining the criterion of maximizing energy efficiency, the departure and arrival date are chosen, fixing thus the total Δv required. These data are summarized in Table 13:

Table 13. Interplanetary transfer data

Departure date	Arrival date	Time of flight	Total Δv	Initial Δv	Final Δv
3/9/2037	11/4/2038	220 days	7.008 km/s	4.372 km/s	2.683 km/s

With these results, it is possible to present the interplanetary transfer trajectory, presented in Figure 31.

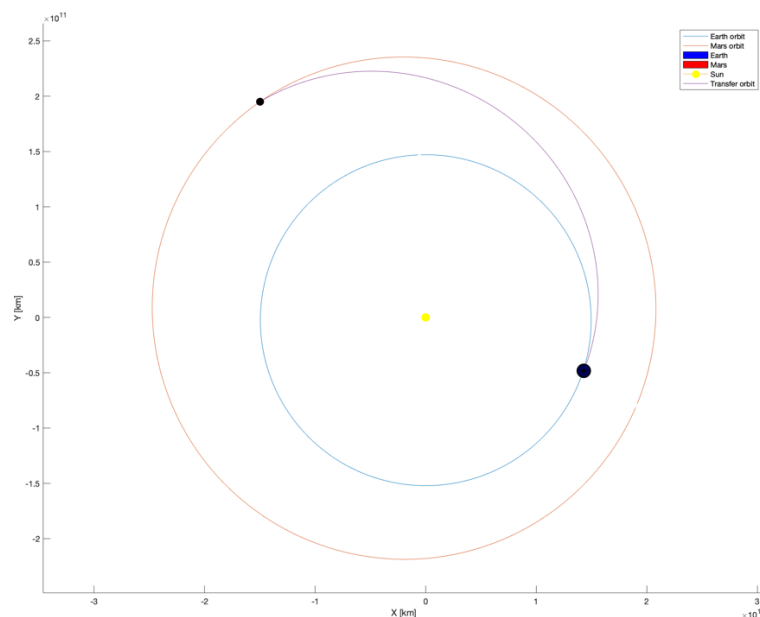


Figure 31. Interplanetary transfer illustration

The characteristics of the transfer orbit are presented in Table 14:

Table 14. Interplanetary transfer orbital elements

e	0.2521
i [°]	3.2437
Ω [°]	18.6552
ω [°]	13.1919
a [km]	200634646
v_0 [°]	13.4728

Once the interplanetary transfer has been defined, it is possible to obtain the departure and arrival hyperbolic trajectories. Both are presented in Figure 32 and Figure 33.

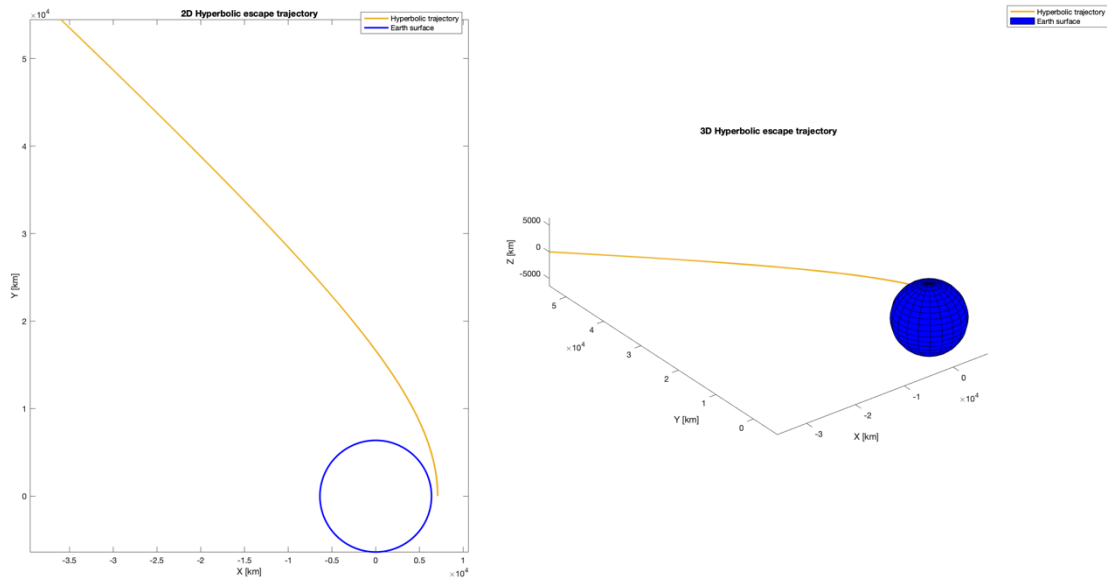


Figure 32. Escape hyperbolic trajectory

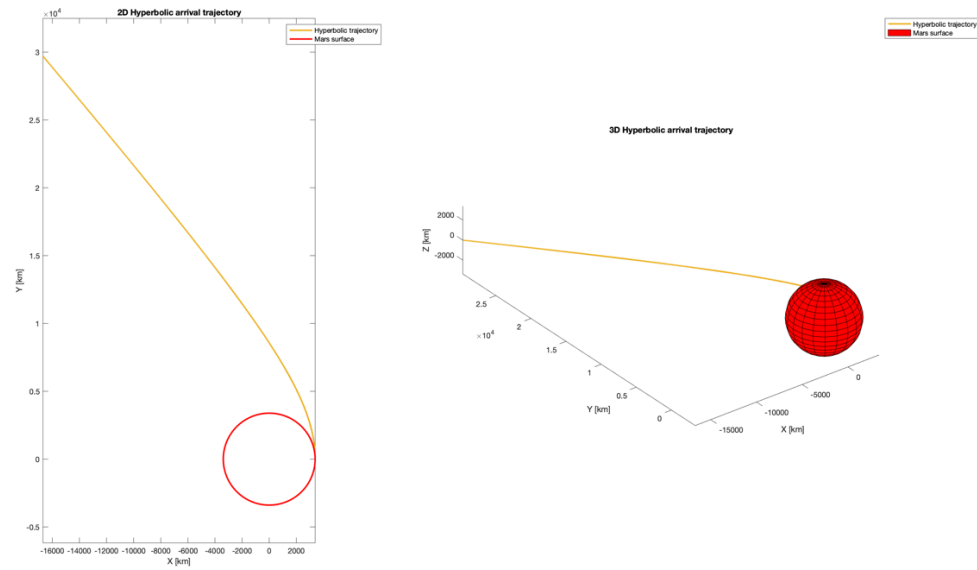


Figure 33. Arrival hyperbolic trajectory

The characteristics of each hyperbolic trajectory are presented in Table 15:

Table 15. Hyperbolic escape and arrival main characteristics

Characteristic	Hyperbolic escape	Hyperbolic arrival
e	1.3512	1.5279
Initial/Final height [km]	700	0
β [°]	42.2606	49.1199
a [km]	-20155.29	-6419.37
p [km]	16641.98	8567.19
h [km ² /s]	81446.27	19155.10

The next study conducted is the launching. The parking orbit where Starship is first launched is at a height of 700 kilometres. There, it will wait for being refuelled. The inputs required for conducting the launching study are available at Table 6. In Figure 34, the time evolution for height, velocity and flight path angle are presented.

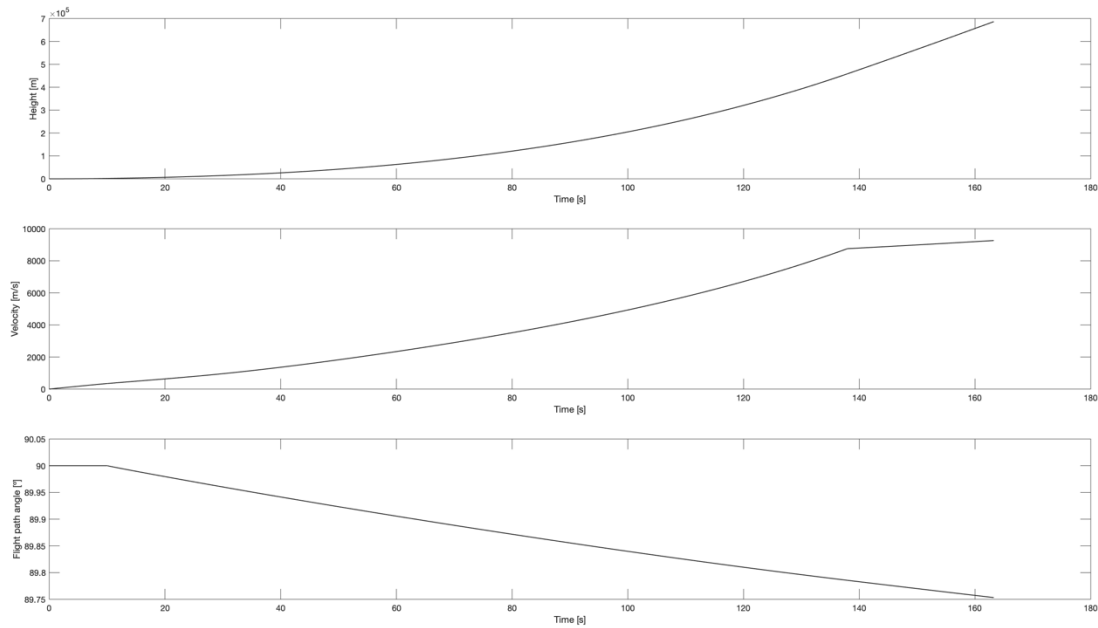


Figure 34. Starship launching study

As it is known, once the Starship is launched it has to be refuelled by four uncrewed configuration Starships. Therefore, it is necessary to perform a rendezvous and docking manoeuvre so as to refill the main spacecraft. It should be noted that the docking manoeuvre is not considered in this thesis. As for the rendezvous manoeuvre, the main data obtained from the study are presented in Table 16, along with the orbital elements of the elliptical transfer.

Table 16. Rendezvous manoeuvre study data

Initial parking orbit height [km]	100	e	0.0443
Final parking orbit height [km]	700	a [km]	6778.14
Initial impulse velocity [m/s]	171.71	p [km]	6764.86
Final impulse velocity [m/s]	167.95	i [°]	0
		Ω [°]	0
		ω [°]	0

The results obtained for the refuelling rendezvous manoeuvre are presented in Figure 35.

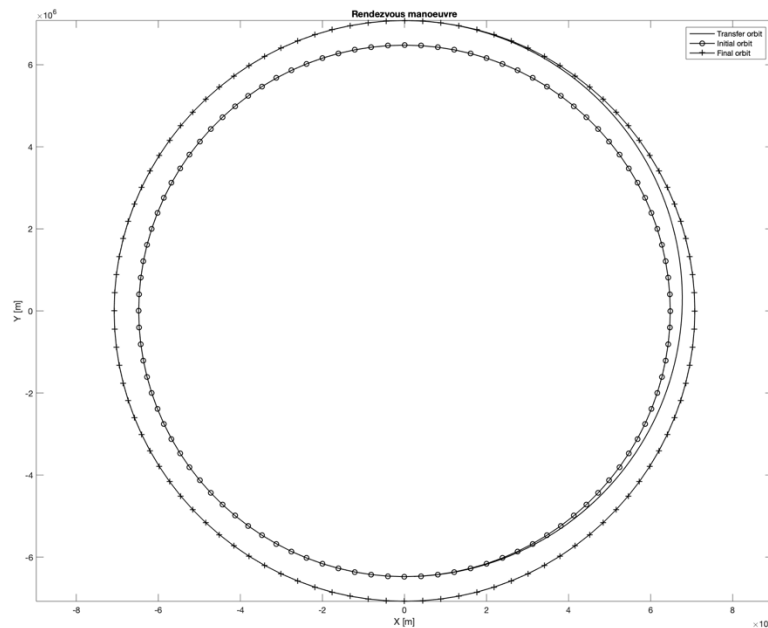


Figure 35. Refuelling rendezvous manoeuvre

Once the required Δv for performing each Hohmann transfer is obtained, considering that four manoeuvres are required per Starship, the total Δv for conducting the refuelling phase can be obtained, presented in Table 17.

Table 17. Total impulse velocity for performing refuelling manoeuvre

Initial Δv [m/s]	Final Δv [m/s]	Total Δv per one Starship [m/s]	Total Δv for refuelling manoeuvre [m/s]
171.71	167.95	339.67	1358.64

Finally, the re-entry study is presented. As commented before, it was not possible to obtain satisfactory results for the re-entry process into Mars. However, the structure developed for solving this phase is able to obtain valid results for the Starship re-entry process into the Earth. Therefore, for the study of this phase, results are presented on the Starship re-entry phase on Earth. Thus, it remains as a point to work on in the future to continue iterating on the structure developed for the re-entry phase in the Mars environment. In Figure 36 and Figure 37 the results are presented for a ballistic entry and for a manoeuvring entry, respectively.

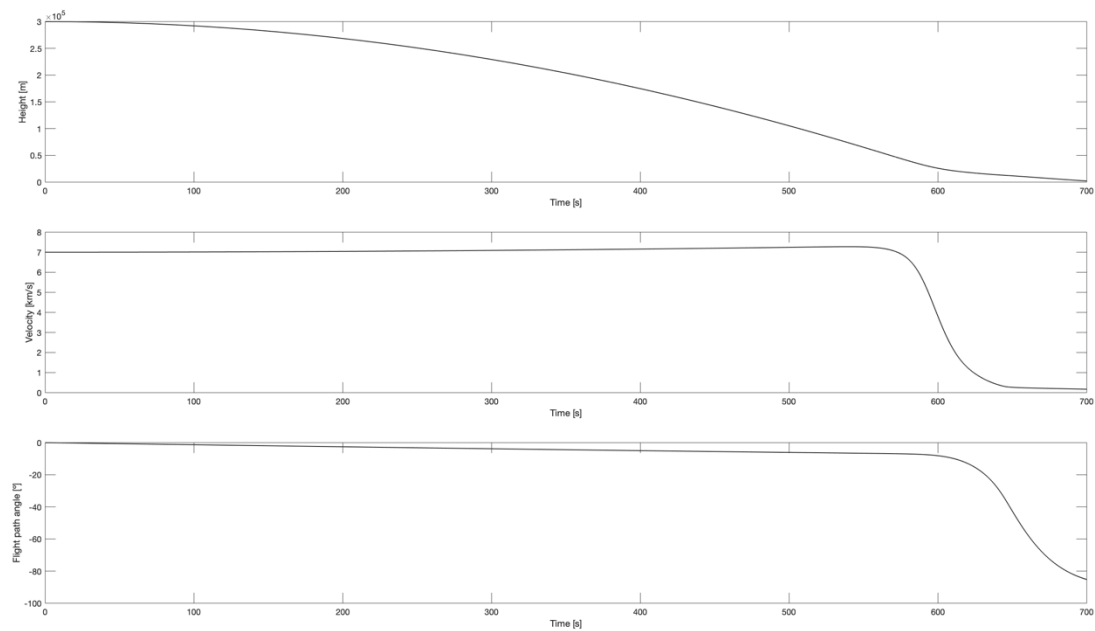


Figure 36. Ballistic entry study

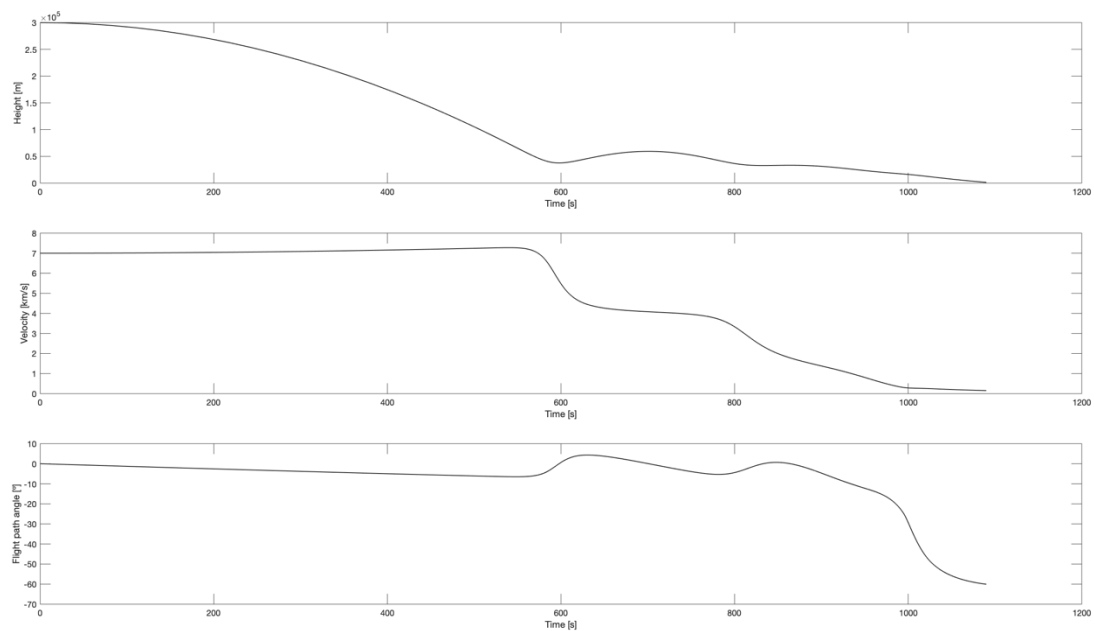


Figure 37. Manoeuvring entry study

5 DEDICATED SPACECRAFT SUBSYSTEMS DESCRIPTION

After the mission analysis performed in sections 3 and 4, the next step of the present thesis is to describe the different subsystems that will form the essential systems of the Starship program. Throughout the following sections, those elements that are already definitive in design and functionality, such as the spacecraft, the propulsion system, the generation and storage of electrical power, or the launch and assembly facilities will be analysed. On the other hand, the possibilities that exist to solve important issues in an interplanetary spacecraft such as the orbital adjustment or the attitude sensing and control will also be described. Finally, the process of obtaining fuel on the Mars surface will be described, since it is an essential process to ensure the success, not only of the SpaceX mission, but also of the interplanetary program.

5.1 PROPULSION SYSTEM

The definition of a propulsion system is a group of elements the objective of which is to drive the vehicle by providing an increase in its mechanical energy (depending on the situation, said impulse can be used to increase the kinetic or the potential energy). In the case of a spacecraft, there are different situations in which a relative impulse is needed, such as taking it into a determined orbit, escaping from a sphere of influence of a celestial body or conducting a trajectory change.

It is important to differentiate the two possible propulsion types that a spacecraft will need to produce during its lifetime – the planetary-atmospheric propulsion and the in-space propulsion. The main difference between these two types is the environment in which the propulsion must be produced; that is to say, in a planetary atmosphere or in the vacuum of space, respectively.

With regard to atmospheric-planetary propulsion, the commonly used method is the use of reaction engines, which normally incorporates rockets. This method provides propulsion by expelling reaction mass through a chemical reaction, following the principle established in Newton's third law of motion. There are other propulsion possibilities such as duct engines, hall effect thrusters, ion drivers and mass drivers. However, the use of these methods is not widespread, because they are either not valid for space propulsion, or at the moment not enough progress has been made in their technology.

On the other hand, the technologies for the in-space propulsion are also very varied. Again, reaction engines can be used. It should be noted that missions have been carried out in which the probe was propelled with electric energy, and even proposals have been carried out which involve solar sails. Other possibilities have been proposed involving nuclear energy, equipping the spacecraft with fission reactors. There is also the option of nuclear fusion, which still awaits practical demonstration on Earth, and by now it represents a good path to investigate for the future.

Be that as it may, SpaceX is developing new technology for both the planetary-atmospheric and the in-space propulsion. For the planetary-atmospheric propulsion, the company is developing a huge rocket called Super Heavy (see Figure 38), the first stage of the Starship spacecraft, which represents the next generation launch vehicle of SpaceX.

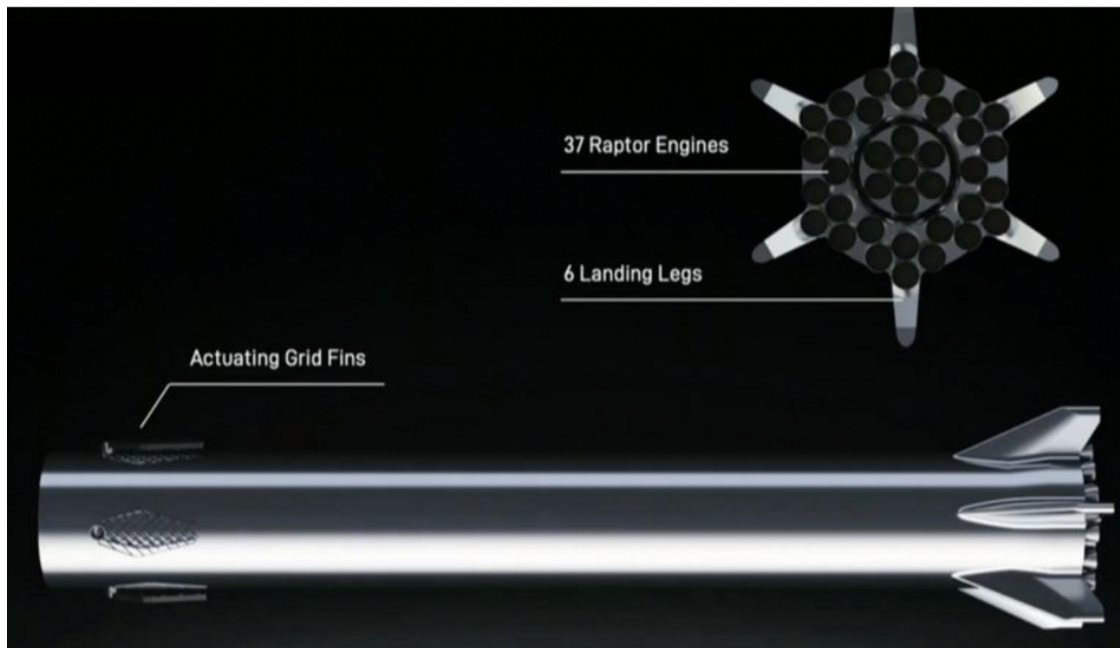


Figure 38. SpaceX Super Heavy rocket [11]

It has a gross lift-off mass of over 3 million kilograms, and it uses sub-cooled liquid methane and liquid oxygen (CH_4/LOX) propellants. It is important to note that it will be a reusable booster, which will return to land at the launch site on its 6 legs. With 9 metres of diameter and 68 metres of height, it will have capacity for a total of 3,300 metric tons of propellant. And regarding the propulsion method, it will use reaction engines, but unlike Falcon 9 or Falcon Heavy launchers, which used Merlin engines, Super Heavy will use the new engines developed by the company, the Raptor engines (see Figure 39), which are full-flow, staged combustion rocket engines, with 1.3 and 3.1 metres of diameter and height respectively, able to produce up to 2 meganewtons. Specifically, 37 raptor engines will be implemented in this launcher, producing a total of 72 meganewtons of thrust jointly, and thus making it the most powerful launch vehicle ever developed.

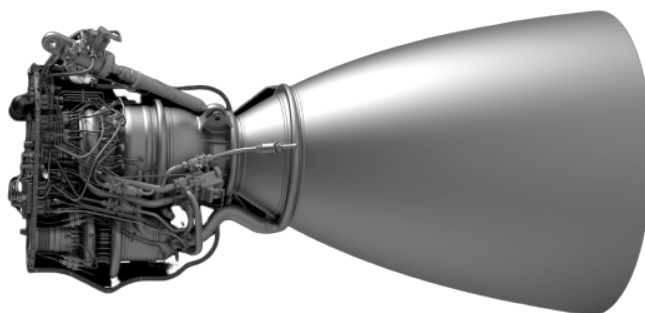


Figure 39. SpaceX Raptor engine [5]

Regarding the in-space propulsion, a total of 6 raptor engines will be installed on the Starship, 3 of them developed for acting at sea-level conditions (intended for manoeuvres such as taking off from Mars surface or landing operations). With respect to the other 3, they are optimized for propulsion in the vacuum of space (see Figure 40). All six engines are capable of gimballing, rotating up to 15 degrees

around its gimbal axis. This capacity allows to control the orientation of the spacecraft through the thrust that produce the engines.



Figure 40. Starship in-space propulsion configuration [11]

It is estimated that Starship will have a capacity for 1,200 metric tons of fuel, and therefore, added to the fuel capacity of the Super Heavy rocket, it brings the total quantity to close to 5,000 tons, which means about 2,000 tons of fuel more than the Saturn V could store. This data is representative of the huge propulsion system in which SpaceX is working in order to carry out the mission.

5.2 SPACECRAFT

A spacecraft is a vehicle design to travel into outer space. The main purposes of this type of vehicle are communication, Earth observation, meteorology, planetary exploration and transportation of cargo and humans. They can be classified into two groups: manned and unmanned spacecraft; and, as this thesis is focused on planetary transportation, it is appropriate to mention the most relevant crewed spacecraft that have flown in history. This spacecraft was the one used by the American astronauts in the Apollo 11 mission, and it was made up of three elements: The Command Module Columbia, the Service Module and the Lunar Module Eagle. It was able to provide a self-sufficient place for working and living during the journey to reach the Moon.

As commented before, there is a lot of variety among the existing spacecraft today, but with Starship, SpaceX is aiming to revolutionize space transportation. Starship is a fully reusable spacecraft, which has 9 metres of diameter and 50 metres of height, and it has integrated a payload section, with a capacity for storing more than 100 metric tons. In Figure 41 both the crew and uncrewed configurations of Starship are presented [5].

One of the aspects that attracted most attention of this novel spacecraft design is a peculiar glossy appearance that gives the feeling that everything has been built with aluminium. However, it is actually a special stainless-steel alloy (called 301), made of nickel and chrome. The company explained this steel becomes stronger when subjected to low temperatures, and furthermore, it can be smelted to be reused in case the rockets are damaged upon returning to Earth. In addition, it facilitates the manufacture and assembly process of the spacecraft, since the characteristics of this material are favourable for welding

operations. Moreover, it is able to withstand high temperatures, so there is no need to add any heat shield on top. Only a thin layer of insulation is added to the part of the rocket that is most exposed when it re-enters the Earth's atmosphere. Another eyecatcher elements are the fins of the Starship, two at the bottom and two others at the top, which will be used to control the spacecraft attitude during landing, as well as to perform certain manoeuvres.

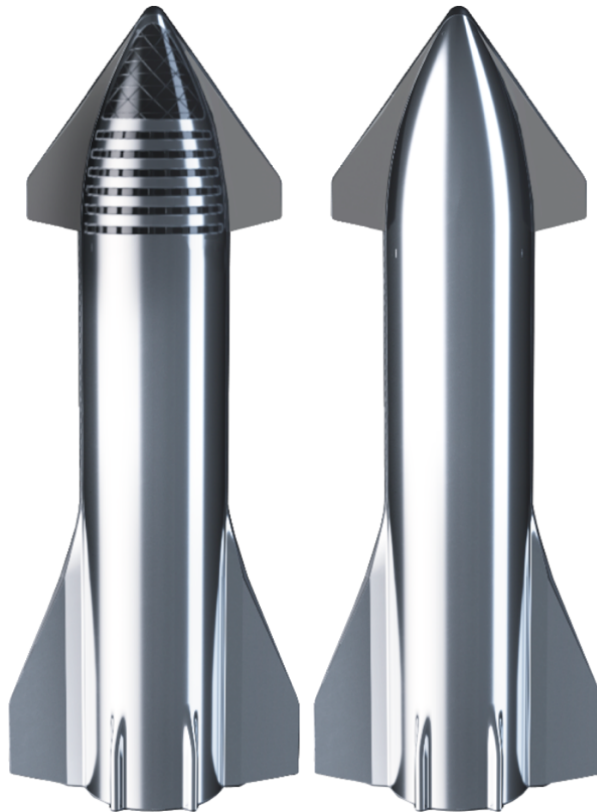


Figure 41. Starship crewed (left) and uncrewed (right) configurations [5]

Regarding the internal structure of the spacecraft, it is divided into two differentiated modules, the cargo area and the propulsion area. In Figure 42 are presented schematically both areas, and the main characteristics of each one is briefly described below.

With respect to the cargo area, it has a pressurized volume of 825 cubic metres, being capable of carrying a huge amount of payload. In a transfer to Mars, the journey could last between three months (in an optimistic scenario) and six months, and therefore the astronauts will need not just a seat but a cabin. In its Mars transit configuration, Starship has a total of 40 cabins, each of them being able to accommodate six people in each of them. Nevertheless, the company expects to host two or three people for cabin, transporting as much as one hundred people per travel to Mars. As mentioned in previous sections, the solar radiation is a troubling effect on the outer space, and for this reason it is needed to implement a solar storm shelter, so as to protect the astronauts in case of a high radiation event occurs during the trip. This shelter is located next to the galley and the entertainment area.

As for the propulsion area, this contains the engines and the propellant tanks. It is important to note that, when the sub-cooled methane and the liquid oxygen are chilled below its liquid point, the density

of both substances increase. This variation must be considered on the tanks dimensioned, as the density increase is on the order of 10 to 12 percent. The company expects to carry 860 tons of oxygen and 240 tons of methane. Another situation that has to be taken into account is the propellant distribution in function of the spacecraft attitude, since in landing operations the orientation may change significantly. It is important to ensure a good propellant transfer to the engines, and therefore the liquid cannot be sloshing around all over in the main tanks. In order to avoid this situation, Starship has implemented two header tanks, one for each substance. These header tanks are capable to feed with propellant the main engines with high precision in every manoeuvring the spacecraft is conducting.

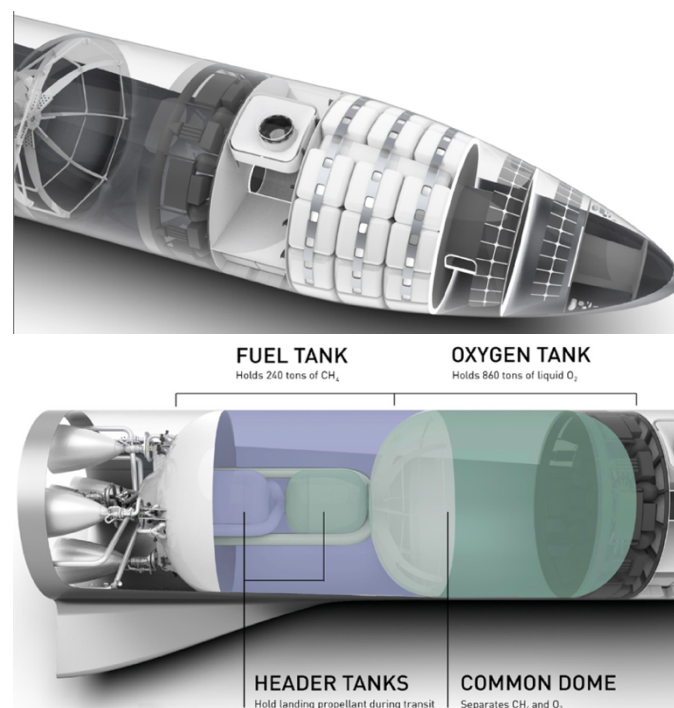


Figure 42. Starship internal structure [5]

(a) Cargo area (b) Propulsion area

In the matter of the possible uses that SpaceX will give to Starship, as a large long-duration spacecraft, there are four in-space options, which are described below. These applications are graphically represented in Figure 43. On the other hand, it should be noted that SpaceX also offers functionality for Starship on Earth, as the company aims to establish the ship as a ground transportation method, connecting places separated by a long distance in a much less amount of time than is necessary to carry out this type of journey at present – this functionality has been named as Starship Earth to Earth.

Satellite deployment

One of the main objectives when designing Starship and Super Heavy rocket was to reduce the marginal cost per launch of the set. With its large payload transport capacity, Starship will be able to deliver satellites to Earth orbit and beyond, with the added value of being able to send huge items with just one launch.

Space Station missions

Starship is designed for delivering both cargo and astronauts to and from the International Space Station. The forward payload volume of the spacecraft is about 1,100 cubic metres, and the aft cargo containers can host a variety of payloads depending on the ergonomics of the objects. Therefore, the spacecraft provides significant capacity for in-space activities.

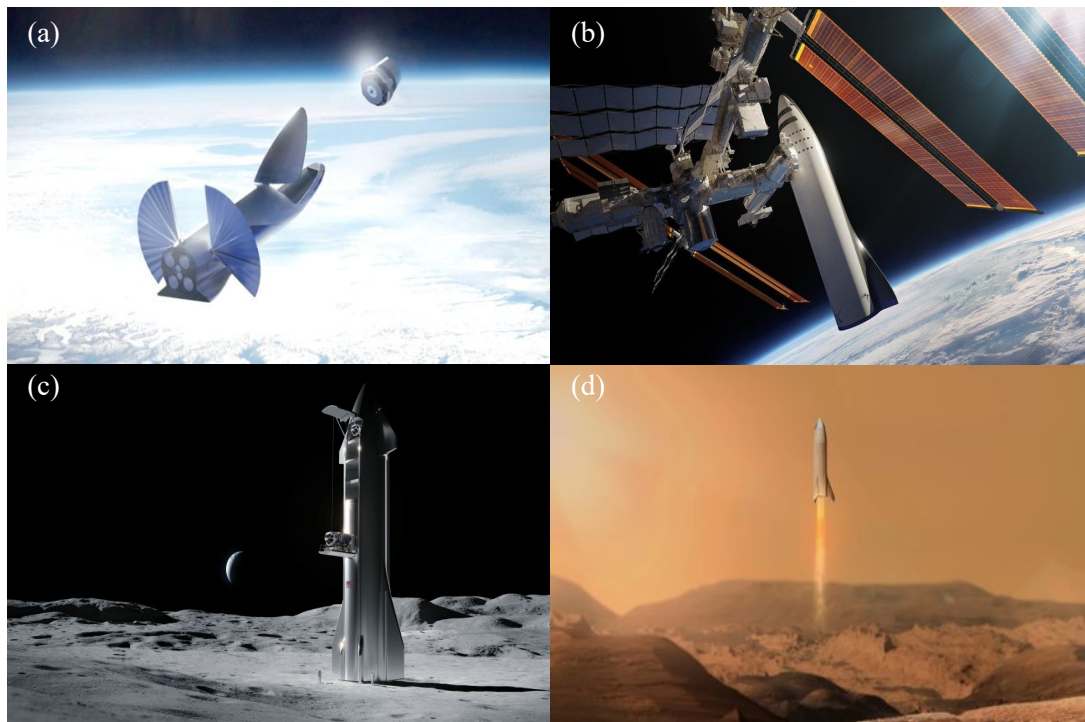


Figure 43. Starship in-space applications [5]

(a) Satellite deployment (b) Space Station missions (c) Moon missions (d) Interplanetary

Moon missions

Arriving to the Moon for building bases, so as to support farther celestial bodies exploration, as well as to conduct experiments on the natural satellite, requires the transport of large amounts of cargo to its surface. SpaceX will help in this scenario acting as a transportation company, by carrying the heaviest objects, such as the building blocks needed to enable a Moon base, due to the great storage capacity the Starship spacecraft provides. It will be also useful for testing the development of the propulsive landing systems, so as to make this future a reality.

Interplanetary transport

In order to achieve the ultimate goal of the Starship program (that is to say, building a sustainable city on Mars), it is needed to deliver large quantities of cargo, and, once a preliminary base has been built, astronauts. Starship is capable to transfer over 100 metric tons of useful mass to the Mars surface, and with respect to sending people, this spacecraft is designed to transfer as many as 100 astronauts on interplanetary flights.

5.3 LAUNCH AND ASSEMBLY FACILITIES

Due to the large size of the Starship and the Super Heavy rocket, SpaceX has to readapt both its launch and assembly facilities. As for the assembly facilities, SpaceX is working at Boca Chica, in Texas, and at Cocoa, one of its development facilities, in Florida. The company is building Starship elements in both factories, in order to produce as much prototypes as possible in the shortest time. It is important to note that SpaceX is also planning to expand their production capabilities by building a new assembly facility in the Port of Los Angeles, which would have 200,000 square metres for building Starship spacecraft. Nonetheless, this infrastructure expansion has not been confirmed by now. The company has been able to manufacture three prototypes of Starship; in Figure 44 the Starship Mk1 is shown.



Figure 44. Starship Mk1 at Boca Chica [2]



Figure 45. SpaceX Cape 39A adapted for Starship [2]

On the other hand, SpaceX has three active launch facilities nowadays: Cape Canaveral Air Force Station, Vandenberg Air Force Base, and Kennedy Space Centre. In the future the current assembly facility of Boca Chica will be adapted to function as a launch facility as well. The company believes that they can optimize their launch operations and reduce launch costs, by dividing their launch missions amongst these four launch facilities. In Figure 45 is shown the adaptation of the Florida LC-39A launchpad for Starship launch and landing operations, at Kennedy Space Centre.

When regarding to build such technological advanced vehicles, which will carry human beings, it is crucial to ensure their reliability. Therefore, testing is vital for their correct development. Currently, SpaceX is testing Starship and Super Heavy rocket components in several facilities; McGregor and Cameron County, in Texas, and Space Coast in Florida are the main locations. Simultaneous operations for Starship testing are being conducted so as to progress in the development of new components, ensuring the functionality of those already manufactured.

5.4 ATTITUDE SENSING AND CONTROL SYSTEM

Attitude control is the process of acting on the orientation of the spacecraft with respect to a specific reference system. In this way, it is possible to place certain elements that need a concrete direction in the optimal position to perform their function. Controlling spacecraft attitude requires sensors to detect the state of the spacecraft's attitude in all situations, actuators which are used to direct and stabilize the

vehicle in a specific direction, and finally algorithms that determine the use of these actuators based on the data obtained from the sensors. The concrete field that studies the combination of these elements is called GNC (guidance, navigation and control) [9].

As for the sensors, there a lot of possible options. They can be divided according to whether they are used for attitude sensing or attitude determination. On the one hand, the sensing sensors could be relative attitude or absolute attitude sensors, depending on whether the generated output is a relative change in the spacecraft's attitude, or the position or orientation of objects, fields or other phenomena outside the spacecraft, respectively. The most common sensors are gyroscopes, motion reference units (such as dynamic positioning sensors), horizon sensors, orbital gyrocompass, earth sensor, sun sensor, magnetometer and star tracker [6].

The final configuration of the sensors that Starship will implement has not been released at the moment this thesis is being performed. However, due to the fact that it is a spacecraft created to carry out interplanetary missions, and analysing the specific architecture that will follow on its way to Mars, it is possible to conclude that it must implement at least the sensors which can be seen in Figure 46.

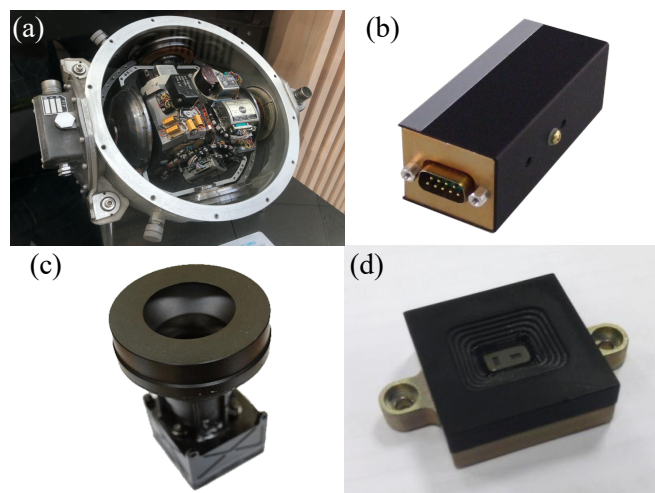


Figure 46. Spacecraft Sensors

(a) IMU [18] (b) Magnetometer [16] (c) Star tracker [15] (d) Sun sensor [17]

IMU

The IMU provides data regarding the Euler angle, using an accelerometer and a gyroscope. It is important to highlight that this device does not require any external information, that is to say, it provides outputs by its own. For that reason, it is really important to calibrate it, as the information it gives is not influenced by any data and cannot be filtered. As it is crucial for any spacecraft, it is important to provide redundancy for ensuring the obtainment of the relevant information provided by this sensor.

Magnetometer

The magnetometer is a device capable to capturing magnetic field strength data and, if it is used in a three-axis trihedron, it is able to provide magnetic field direction outputs. As Starship will be orbiting around the earth, waiting for being refuelled, it is a good way to determine the spacecraft attitude by

comparing the sensed magnetic field strength to a map of Earth's magnetic field, which could be stored in the memory of a ground-based guidance computer.

Star Tracker

A star tracker is an optical device which uses photocells or a camera. Using the magnitude of the brightness and the spectral type, it is able to identify and calculate the relative position of the stars around the spacecraft. It could be used to determine the attitude of Starship from the moment it has started the transfer to Mars – and therefore has lost the reference to the Earth's magnetic field – until the moment it lands on the Martian surface.

Sun Sensor

A sun sensor is a device capable of sensing the Sun direction. It will be used during all the mission, providing attitude information obtained from the solar radiation information captured. This sensor could be made up of solar cells and shades, or it could have more complex structure, similar to a steerable telescope.

Once the configuration of the sensors is defined, it is possible to determine how the attitude of the spacecraft will be acted upon. In order to change the spacecraft attitude, it is needed to be aware of the current spacecraft attitude. Therefore, is helpful to use a statistical filter so as to get a normalized value for the attitude, obtained from a set of measurements which have been captured by the different sensors. The most common used is the Kalman filter.

Regarding the spacecraft actuators, there are several mechanisms that could be used in a spacecraft. The most important are thrusters, momentum wheels, solar sails, spin stabilization and magnetic torquers. It is important to remark that thruster systems have been used on most manned space vehicles, including the Apollo program vehicles. However, they have an important drawback, which is the fuel limitation on mission duration. Thus, auxiliary actuators may be used in order to reduce vehicle rotation, such as an ion thruster, which accelerates ionized gases electrically to extreme velocities, being powered by solar cells.

In the case of the Starship, it will implement methane and liquid oxygen pressure fed hot gas thrusters for attitude control. This ACS (Attitude Control System) will be used for conducting the necessary attitude control actuations, including the trajectory corrections – so as to counter-act the disturbance torques that affect the spacecraft in its space environment – and the final pre-landing pitch-up manoeuvre, in which the spacecraft must rotate almost 180° so as to land in the desired position. Starship initial prototypes are using nitrogen cold gas thrusters, which have a substantially less mass efficiency. Nonetheless, these thrusters are expedient for quick manufacturing and support early prototype flight testing. In Figure 47 can be seen two thrusters belonging to the Starhopper ACS.



Figure 47. Starhopper thrusters [2]

It is also worth to note that the company has indicated that the two fins installed on the lower section of Starship are steerable, allowing to control its attitude in atmospheric environment. Furthermore, a smaller fin would be added, but it will not be steerable; in fact, it will be used as a landing leg and

therefore it will not be an element of attitude control. As for the stability during take-off and landing operations, it would be controlled by the rapid movement of rear and forward fins, and in case it is needed, it will be able to use the thrusters.

5.5 ELECTRICAL POWER GENERATION AND STORAGE

The Electrical Power System (EPS) is the system destined to supply continuous electrical power to the subsystems as needed during the entire mission life. Thus, it is really important to consider how to generate electrical power in those phases in which it is possible to do so, and for those in which it is not, it is necessary to implement energy storage options [13].

Engineers constantly try to increase performance of power system, which usually is the heaviest equipment of any spacecraft. The current state of the art for the spacecraft power generation are the triple junction solar cells, but they will be replaced by four to six junctions coming soon. On the other hand, there is the possibility of implementing fission nuclear reactors as the power generation source, which provide much more power than solar energy. Notwithstanding, for manned missions it would be needed a shield of large dimensions, which further increases the weight of the system. In the matter of power storage, the Li-ion batteries are currently the most efficient and those that have a more widespread use. However, new battery technologies, like Lithium-Sulfur, are the subject of intense efforts to provide a new step forward in terms of energy density.

In the case of Starship, the power generation will be provided by solar panels that, according to what the company has indicated, will be able to generate a quantity of power on the order of 200 kilowatts. As for the batteries, the company is taking advantage of the technology developed by Tesla, an electric car company that shares the founder with SpaceX. Although initially seems surprising to use the batteries of a car in a spacecraft, after delving into the technology of these energy storage systems, it is a quite logical decision. By using Tesla battery systems, which have industry leading power management capabilities, SpaceX saves a great amount of money, effort and time. In addition, the possibility that the company tries to modify batteries derived from those used by Tesla and certify them as battery packs for use on orbital missions is raised as an option for the future. Figure 48 shows the Starship spacecraft with solar panels deployed once it has started its trajectory to Mars (left), as well as the mounting of multiple Tesla battery packs on a Starship Mk1 header tank (right).



Figure 48. Starship solar panels and battery pack [4]

5.6 FUEL GENERATION ON MARS SURFACE

SpaceX ultimate goal is to build a sustainable Martian city, and in order to accomplish it, it is necessary to achieve abundant traffic between the Earth and Mars. Therefore, it is essential to find an optimal way for obtaining fuel on the red planet. The company has proposed the Sabatier reaction as the solution, as commented in previous sections, and is currently investigating this process so as to carry it out in Mars [14].

The main reason for using this method is the fact that it incorporates in situ resource utilization (ISRU), which allows reducing the cost of human missions to Mars – ISRU is the practice of collecting, processing, storing and using materials found or manufactured on astronomical objects (such as planets or natural satellites), that are used for replacing materials which otherwise would be brought from the Earth.

The Sabatier process consists in the reaction of hydrogen and carbon dioxide at high temperatures (between 300 – 400 °C) and high pressures, so as to produce methane and water. In order to increase the rate of the reaction, it could be added nickel as a catalyst. The process is described by the next exothermic reaction:



The dioxide oxygen is obtained from the Mars atmosphere, and as for the hydrogen, it can be obtained from an electrolysis process (that separates hydrogen and oxygen from water). The water needed for the electrolysis can be obtained from the subsoil, as water ice. However, to carry out the hydrogen obtainment by electrolysis, it is necessary to have a developed infrastructure, since the energy required to obtain the fuel through the whole process is increased. Therefore, initially the hydrogen necessary to carry out the Sabatier reaction could be transported from Earth. As for the resulting chemicals, the methane is stored as fuel and the water can be stored to be used in other processes, such as agriculture or consumption thereof, as well as to use it again in electrolysis and thus obtain oxygen and hydrogen, closing the continuous cycle. The overall rate expected from the optimised fuel obtainment system is one tonne of propellant per 17 MWh energy input, obtained through solar panels.

It is important to note that the Sabatier process is currently used in space; NASA uses the Sabatier reaction to recover water from astronauts exhaled carbon dioxide and the hydrogen previously stored from electrolysis on the ISS – electrolysis is used in ISS for obtaining oxygen for astronauts to breathe. Regarding the produced methane, it is released into space. While it is true that the environment of the ISS has nothing in common with that of Mars, the fact that this process is already being used in space provides reliability when opting for it.

6 MARS SOCIETY COMPETITION CASE STUDY

The Mars society presented in February 2020 a new international contest for the best design plan of a Mars city state, with 1,000,000 habitants on it [27]. The winning team will be awarded with 10,000 dollars, and what is more, the best 20 proposals will be published in a new book named as '*Mars city states: new societies for a new world*'. As for the requirements of the competition, it is important to remark that the proposed model city should be as self-supporting as possible – i.e. taking the maximum profit of the in-situ resources available in Mars, and thus relying on a minimum mass of imports from the Earth.

The director of this final degree project, who is part of a team that is participating in the contest described above, proposed to its author to participate in the competition, due to the synergy existent between the work that has been developed during the thesis and the Earth-to-Mars transfer system section necessary for the competition – which is essential in the development and growth of the proposed Martian city. Specifically, the section 0, in which a detailed description about Starship and the Super Heavy rocket is done, represents a really good input for performing the case study described in this section. Thus, the proposal was received as a great opportunity for being part of an amazing challenge and was accepted.

The team begins the study starting from a colony of 1,000 habitants on Mars in 2100, and the goal is to reach one million habitants by the year 2150. The architecture that allows achieving this goal had already been developed by the team, consisting of a bilateral transportation system: shuttles similar to Starship with capacity for hosting 200 and 500 passengers, and a huge space station which is orbiting in such a way that it performs fly-by manoeuvres around the Earth and Mars periodically – named as EMTS.

On the one hand, the shuttles follow an architecture similar to the one planned by SpaceX with Starship: the shuttle is launched to a parking orbit where it waits for being refuelled, and then it starts the interplanetary transfer for finally landing on Mars. On the other hand, another shuttle configuration is launched so as to perform a rendezvous and docking manoeuvre with a huge spacecraft, with capacity for transporting thousands of people. Once the people have been transferred to the mentioned spacecraft, it performs a rendezvous and docking manoeuvre with the EMTS, and then it returns to the initial orbit for waiting more shuttles. When the EMTS is full of people, the interplanetary transfer starts and then, the landing on Mars is performed in several capsules preinstalled in the EMTS.

It should be noted that all the shuttles are launched from the Earth with a first stage reusable booster, similar to the Super Heavy rocket, while for performing the launching from Mars, it is not necessary the use of a booster, as the gravity field on Mars is weaker than on the Earth.

The main goal of the study described in this section is to obtain the first iteration for the total amount of main materials necessary to build the shuttles and launchers to conduct the people-transfer from Earth to Mars. It is important to remark that, as there are several options for the EMTS' development but it has not been defined yet, it is not considered in this case study.

To do so, the inputs are the total weights of Starship and the Super Heavy rocket, and the weight budget percentages (% of payload mass [26]) used for estimating the weight of each subsystem of the elements, presented in Table 18 and in Table 19, respectively.

Table 18. Starship weight estimation and main materials weight

Data	Estimation (% of Payload Mass)	Mass [kg]	Material	Mass [kg]
Dry Mass of Starship	—	1200000	Stainless-steel	75000
Payload	100	100000	Carbon fiber	129000
Structures	75	75000	Liquid oxygen	936000
Thermal	16.1	16100	Methane	264000
Power	21.4	21400		
TT&C	16.1	16100		
Attitude Control	21.4	21400		
Margin	28.6	28600		
Propellant Tanks	10% of propellant mass	120000		
Propellant Mass	—	1200000		
Engines	6 raptor engines	9000		
Gross Mass	Sum of subsystems	1727600		

Table 19. Super Heavy rocket weight estimation and main materials weight

Data	Mass [kg]	Material	Mass [kg]
Dry Mass of Super Heavy	244500	Stainless-steel	230000
Structure	230000	Carbon fiber	355500
Propellant Mass	3000000	Liquid oxygen	2340000
Engines (37 Raptor engines)	55500	Methane	660000
Tanks	300000		
Gross Mass	3830000		

As for the materials used in Starship and Super Heavy, it should be remarked that there is no specific description of the involved materials for each system. The known materials for the construction of both vehicles are stainless-steel for the structure, carbon fiber for the propellant tanks, and liquid oxygen and methane as fuel. The proportion of liquid oxygen and methane is a 78:22.

By using a rough weight scaling of the subsystems of the spacecraft and the rocket, depending on the passengers capacity of each global system and assuming a security coefficient of 1.5, it is obtained the weight budget for the different shuttles and launchers used in the architecture. It is worth to mention that the architecture proposed determines the total number of shuttles and launchers required for achieving the desired Mars population evolution. All the shuttles and launchers considered in the study, as well as the necessary quantity of each type are presented and described in Table 20.

Table 20. Vehicles needed for conducting the architecture

Type vehicle	Description	Payload [kg]	People capacity	Number of needed vehicles
Shuttle_1	Shuttle used for Earth-Mars/Mars-Earth transfers (reusable)	60000	200	151
Shuttle_2	Shuttle used for Earth-Mars/Mars-Earth transfers (reusable)	150000	500	200
Launcher type I	Launcher used for leaving Mars and docking with EMTS (reusable)	150000	500	467
Launcher type II	Launcher used for leaving the Earth and docking with EMTS (reusable)	150000	500	467

The mass of main materials needed for manufacturing one unit of each type of vehicle is presented in Table 21.

Table 21. Main materials for building one unit of each type of vehicle

Type Vehicle	Stainless-steel [kg]	Carbon fiber [kg]	Liquid oxygen [kg]	Methane [kg]
Shuttle_1	556500	1098000	7488000	2112000
Shuttle_2	1391250	2745000	18720000	5280000
Launcher type I	168750	129795	749154	211299
Launcher type II	892267	10341081	4956635	1398025

Finally, the total mass of each main material for manufacture all the required vehicles, as well as the mass per person value, are presented in Table 22.

Table 22. Total mass for manufacturing all needed vehicles

Main materials used in SHUTTLE systems production	Total Mass for all Shuttle_1 [kg]	Total Mass for all Shuttle_2 [kg]	Total mass [kg]
Stainless-Steel	2.78E+08	8.35E+07	3.62E+08
Carbon fiber	5.49E+08	1.65E+08	7.14E+08
Liquid oxygen	3.74E+09	1.12E+09	4.87E+09
Methane	1.06E+09	3.17E+08	1.37E+09

Main materials used launcher I	Mass for one launcher I [kg]	Mass per person [kg]	Total mass [kg]
Stainless-Steel	1.69E+05	3.38E+02	7.88E+07
Carbon fiber	1.30E+05	2.60E+02	6.06E+07
Liquid oxygen	7.49E+05	1.50E+03	3.50E+08
Methane	2.11E+05	4.23E+02	9.87E+07

Main materials used launcher II	Mass for one launcher II [kg]	Mass per person [kg]	Total mass [kg]
Stainless-Steel	8.92E+05	1.78E+03	4.17E+08
Carbon fiber	1.03E+07	2.07E+04	4.83E+09
Liquid oxygen	4.96E+06	9.91E+03	2.31E+09
Methane	1.40E+06	2.80E+03	6.53E+08

Total main materials	Total mass [kg]
Stainless-Steel	8.57E+08
Carbon fiber	5.60E+09
Liquid oxygen	7.53E+09
Methane	2.12E+09

As can be seen from the final results, the required amount of each of the different materials considered is huge. Furthermore, this estimate study has been made assuming that the technology will have advanced enough to make feasible to follow the proposed mission architecture. Therefore, as a conclusion it is derived that the obtained results constitute the first approximation of the preliminary study of the materials analysis necessary to successfully carry out the project. For the next step, the process developed should be iterated by carrying out a more detailed study, defining all the necessary materials for each subsystem.

All the tables developed for preparing the results presented in this section are available in the annexes document.

7 ECONOMIC PLAN

In this section it is presented a preliminary economic plan for carrying out the Mars' colonization process, following the proposal described in section 4. The main goal of this section then is to obtain a global result of total investment required for manufacture and produce all the Starship and Super Heavy rockets needed, and for the total mass of fuel needed for realizing the Earth to Mars transfers.

To do so, the inputs required are the total number of Starships and Super Heavy rockets needed, the total amount of fuel necessary and the cost for producing one Starship, one Super Heavy rocket and the price for one kilogram of fuel (composed by liquid oxygen and methane). The costs for each element considered for estimating the required economic plan are presented in Table 23. It should be noted that the costs for Starship and Super Heavy rocket have been estimated considering a 2 million euros cost for each Raptor engine, because it is the most generalized estimate regarding its average cost, once its manufacture has been industrialized. As for the liquid oxygen and methane cost per kilogram, both have been obtained from the current United States price list, and for obtaining the average price per kilogram of fuel, it has been considered that the ratio mentioned in previous sections is maintained – i.e. a LOX to CH₄ proportion ratio of 78:22.

Table 23. Cost estimation for each element considered

Input	Cost [€]
One crewed Starship	50M
One uncrewed Starship	40M
One Super Heavy rocket	200M
One kilogram of fuel	10.50
One kilogram of LOX	13
One kilogram of CH ₄	1.75

Regarding the number of Starships needed, the total crewed-configuration Starship quantity has been estimated in the previous section, in which an approximation has been done so as to achieve the main goal of creating a Mars' colony of 100,000 habitants by year 2050 – 961 Starships needed. However, for performing this approximation, it was just considered the Starships shipped to Mars, but the number of possible Starships that come back to the Earth was not taken into account. In this section, it is assumed that for each 100 Starships that arrive to Mars, 20 come back to the Earth. Maintaining Starships in Mars is important, since, in the event of any type of issue, it is possible to evacuate the planet. Also, is important to consider that for each interplanetary transfer it is required to launch one crewed Starship, that takes the astronauts, and in addition a total of four Starships in the uncrewed configuration, so as to refuel the first one. It has been assumed that each crewed Starship is able to perform ten interplanetary transfers.

On the other hand, regarding the total number of Super Heavy rockets required, it has been considered that each Super Heavy is capable of making a total of ten complete launches – i.e. take

Starship to the point in which the first stage separation occurs and reenter the Earth's atmosphere to be refuelled and put back into operation. However, as mentioned before, it is also needed to take into account that for each interplanetary transfer, a total of five launches are required.

In the Table 24 the required quantity of Starships and Super Heavy rockets for achieving the Mars' colonization goal are presented. The complete table from which these results have been obtained is presented in the annexes document.

Table 24. Required quantity of Starships and Super Heavy rockets

Vehicle	Quantity
Crewed Starship configuration	761
Uncrewed Starship configuration	305
Super Heavy rocket	385

In order to further detail the economic plan, the required investment in each of the main materials, identified in the previous section, is calculated. It is important to note that a detailed budget is not obtained, since there is no specific data on all the materials used in the manufacture of Starship and Super Heavy rocket. Nevertheless, it is useful to estimate the total cost that is invested in these main materials, so that a study of the price evolution of each of them can be conducted. As can be seen in Figure 49, each material price evolution has a different trend: stainless-steel shows a slight variation over time, fluctuating close to the average price value, in a similar way as liquid oxygen. Aerospace carbon fiber shows a slightly upward trend in last years.

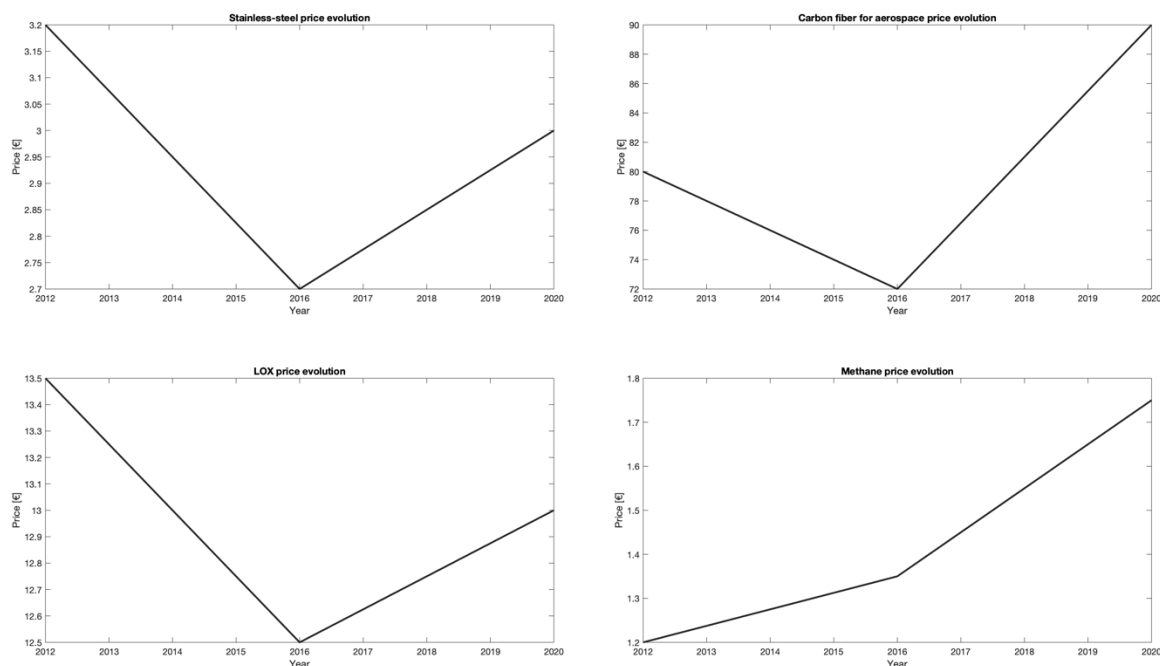


Figure 49. Main materials price evolution

However, the material to which more attention should be paid is methane, as a substantial increase in its price is expected, due to the large depreciation of gasoline as a consequence of the looming economic crisis. The data used for developing this figure is available in the annexes document.

In Table 25, the cost per kilogram of each main material is presented, and by using the weight estimation detailed in previous section, it is possible to obtain the total cost per material for producing all needed Starships and Super Heavy rockets.

Table 25. Main materials cost estimation

Material	Cost per kilogram [€]	Total material mass [kg]	Total cost [€]
Stainless-steel	3	8.00E+07	239,850,000
Carbon fiber	90	1.38E+08	12,376,260,000
LOX	13	8.24E+08	10,706,018,457
Methane	1.75	2.32E+08	406,490,838

Finally, it is presented in Table 26 the total budget required for conducting the colonization process, by using the costs presented in Table 23 and in Table 24 – i.e. taking as inputs the total price for producing one crewed Starship, one uncrewed Starship, one Super Heavy rocket, the total fuel required for performing the interplanetary transfers and the price for one kilogram of fuel (composed by liquid oxygen and methane in a 78:22 proportion, respectively).

Table 26. Total cost

Crewed Starships	Uncrewed Starships	Super Heavy rockets	LOX [kg]	Methane [kg]	Total cost [€]
761	305	385	8.24E+08	2.32E+08	138,362,509,295

8 ENVIRONMENTAL ANALYSIS

This section is addressed to analyse the impact that the proposed architecture for setting up a Mars colony could have if it is carried out and implemented. The analysis of this impact is distributed in three different areas of study: environmental, economic and safety.

8.1 ENVIRONMENTAL IMPACT

The study of the environmental impact is mainly based on how the implementation of the proposed architecture affects directly to the wildlife, vegetation and the planet itself, for both planets involved in this project – i.e. it is going to be considered the impact of the project caused in the Earth and in Mars.

Regarding to the wildlife and vegetation, it is a fact that the urban centres create microclimates (by increasing their average temperature and offer different type of feed possibilities and shelter to different species of animals) and destroys much of the vegetation that initially dominated the land extensions. With the creation of new launch and assembly facilities, the impact to the wildlife would be one or another, depending on the location chosen. To this day, SpaceX is developing its prototypes in already existing manufacture plants, but the impact on the wildlife is greater than it was, due to the growth of activity in these places. With the start of this project, a large number of manufacturing processes and tests are carried out, which alter the surrounding wildlife and vegetation, and these facilities are expected to increase if the project continues. As for the global planet itself, it will obviously be affected by the massive number of launches necessary to achieve the company's ambitious goal of Mars' colonization. The fuel used to propel the Super Heavy rockets produces large amounts of CO₂, a gas that increases the greenhouse effect, and thus accelerating global climate change.

In the case of the environmental impact on Mars, it must be considered that there is no evidence that there has ever been life in the history of the planet. Therefore, it is very important to assess the influence that the human species wants to settle on the planet. Regarding wildlife and vegetation there is no evidence that there is any kind of life on that planet, as mentioned above. For that reason, if no unexpected discovery occurs, there will be no possibility to alter both elements. Another topic to consider is the impact that creating a new ecosystem on the surface of Mars could have, so that the project to build a city on Mars could be carried out. It is important to assess the existing risks of inhabiting a planet where the environment is a constant threat to its habitants, and the risk increases as the number of members within society grows.

All the factors described above require a lot of attention, due to the great influence of a project such as the one analysed in this thesis, and which also affects globally. Therefore, aerospace companies constantly study and develop viable solutions to solve the topics, so as to maintain the balance in the environment.

8.2 ECONOMIC IMPACT

Regarding to the analysis of the economic impact, the most important aspects to consider are the enormous investment necessary to produce all the vehicles necessary to carry out the global project, as well as the needed infrastructure to develop, test and validate them. On the other hand, it should be noted

that, with respect to what it would entail to conduct a project of such a dimension as that proposed by SpaceX, without developing reusable technology, the total investment required would be exponentially higher. Therefore, it should be taken into account that, despite the final number obtained when making an estimate of the required budget, colonizing Mars by using the Starship architecture reduces the cost. On the other hand, space technology has been shown to produce benefits on Earth. In fact, a time is currently underway in which Earth observation projects are gaining in importance, and from these data obtained by satellites and processed on Earth, improvements in the operating processes of almost all sectors can be obtained. Again, there seems to be a global spirit of exceeding established limits, and this is demonstrated by the fact that government institutions are investing large amounts of their budgets in aerospace companies. A great example of this argument is the United States, which has injected 22.6 billion dollars for fiscal year 2020, with the aim of going back to the Moon and encouraging projects like the one analysed in this thesis, where the objective is to reach the red planet.

The impact of deciding to carry out this project in relation to the amount of employment that would be created should also be considered. Therefore, the need for prepared scientists would increase globally and this would undoubtedly benefit in advancing as a society, since the motivation to study scientific careers would grow, as well as its demand, thus causing an increase in the production and exchange of ideas that would provide a great economic benefit.

8.3 SAFETY IMPACT

The last area to analyse its impact is the safety. In terms of safety, the most important aspect to consider is to ensure the survival of astronauts traveling to Mars. For this purpose, all the systems described throughout this thesis have redundancy, so that in the event that something fails, there is a possibility of reaction and solve the issue. It is important to highlight within the different subsystems the life-support system, since it is essential to keep astronauts safe from possible radiation events, in addition to pressurization systems. It is also worth mentioning the importance of ensuring that the propulsion systems are prepared to act with the aim of avoiding any possible collision (with asteroids or even space debris), and stress that the guidance and navigation system is crucial for astronauts to arrive safely to destiny. Nevertheless, it should also be borne in mind that during the launch of the spacecrafts, the first phase is recoverable, and despite the fact that SpaceX has shown to successfully control its recovery, it has never been performed with a rocket of the dimensions of Super Heavy rocket. Therefore, it is necessary to take extreme security measures, in order to prevent the rocket from colliding in an inhabited area. Therefore, the launch pads are strategically located, and the launches take place facing the ocean. On the other hand, during the manufacture of components such as the spacecraft, the rocket and all involved subsystems, it is necessary to ensure the safety of the employees, since they work in dangerous environments handling very heavy structures. It is not the first time that a space-vehicle fails during a test, causing an explosion, and therefore maintaining safety measures is and imperative.

Due to all the described, it is concluded that the main focus is to maintain the safety of people who travel to Mars, since it is the greatest challenge. However, it should not be neglected to take the necessary measures and considerations so that the people who stays in the Earth also maintain their security.

9 CONCLUSIONS, IMPROVEMENTS AND RECOMMENDATIONS

9.1 CONCLUSIONS

After carrying out such a challenge as it is to define and develop an architecture analysis tool for interplanetary transfers, there are different points that should be commented:

- A fully design of an interplanetary mission architecture analysis tool capable to study each of the phases involved has been carried out successfully accomplishing all the requirements previously established. What is more, the scope of the project that was initially set has actually been totally reached and, throughout the development of the project, opportunities arose to develop studies related to the project that were not reflected in the scope, and they have been carried out, adding greater value to the thesis.
- Such an ambitious project has encouraged to the author to its development because of the opportunity to perform a multidisciplinary project, in which fields such as research, mechanics, aerodynamics, astrodynamics, or programming skills are involved.
- During the thesis' development there has been several times in which the technical background of the author was not enough for studying and solving concrete phases, due to the high complexity of the tasks. Therefore, it has been necessary to learn new skills and quickly adapt to new situations.
- Communication with the director of the thesis, despite the global situation in which it has developed, has been constant and fluid, and it has helped to the correct development of the project. As happens in a real project, the communication between all the members who are collaborating on a project is one of the most important keys, and throughout the development of this thesis, this skill has been reinforced.
- This project, which means the end of the grade, has finally given to the student quite valuable experience in project managing, planning, defining the key topics, designing and scheduling, being able to programme interplanetary transfers so as to colonize other planets, estimating the time, resources and main objectives to carry it out successfully.
- The mission architecture to reach Mars proposed by SpaceX is very ambitious; both the spacecraft and the rocket on which they are currently working are large vehicles and must have propulsion methods capable of taking them to their destination. Throughout this thesis, all the phases included in the Starship program have been described in detail and numerically analysed, whose main objective is to colonize Mars, creating the first sustainable extraterrestrial city there. It is true that the investment required for carrying out the project is very high, but if the company is capable of developing the spacecraft and the rocket with the specifications they have defined, the arrival of man on Mars may be very close, since, as has been seen throughout this study, it is a goal perfectly feasible to achieve using the Starship program architecture.
- As for the results, the launch phase, the rendezvous manoeuvre, the interplanetary transfer solving the Lambert problem and the hyperbolic departure and approach all have been successfully analysed and the results obtained have been validated by posing cases with a

known solution and comparing the results obtained through the developed code structure with the existing results. Regarding the re-entry and landing phase, although it has not been obtained the desired results, i.e. entry study in Mars, it has been successfully developed a structure code capable of analysing the entry process in Earth for both a ballistic and a manoeuvring entry.

9.2 IMPROVEMENTS AND RECOMMENDATIONS

Overall, the developed tool accomplishes all the initial requirements set up, and ensures the validity of the results obtained, with a low percentage of errors, based on the performed studies and validation processes conducted. Nevertheless, there are some recommendations for further improvements.

As previously mentioned, the process of entering Mars has not obtained satisfactory results. Mostly, it is because the standard chosen to model the atmosphere of Mars was not as precise as needed, and the gravitational model could not be completed, because the spherical harmonics (or Jefferey's constants) could not be found. As a first step to be taken in the future, it is therefore important to define a better atmospheric model for Mars and calculate its spherical harmonics to obtain the complete gravitational model.

Keeping in mind this first experience with the tool, in other words, what is the system behaviour for analysing a mission architecture, the codes can be a little bit modified and optimized so as to improve and make easier the post process of several data. Mainly, the porkchop plot structure code could be optimized in such a way that it takes less time to carry out the studies, and in turn the graphs could be automated, since it is necessary to carry out the study twice, once for each type of movement (Type I or Type II), save the data obtained from each analysis manually and then plot them.

As regards the Lambert solver, as an improvement is the analysis of the nonlinearities that are obtained, since in the current solver they are avoided and not calculated. For this reason, it would be interesting to develop a function that allows analysing these specific cases, making the program more robust. Also, the techniques that collaborate by iterating in the solver could be an improvement point, since it would be interesting to analyse in detail how to optimize the whole process.

Despite this improvements and recommendations, as already commented, the main objective of this study has been achieved successfully, creating such a valuable mission analysis architecture tool which can be used for obtaining the main results of interplanetary transfer projects, giving the student the opportunity to demonstrate all his skills in astrodynamics and programming, but also in planning, scheduling and main objectives determination applied to the space sector, specifically, space exploration.

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